

MultiUAV2 Simulation Users Manual Version 2.0

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Chapter 1

Background

1.1 Overview

The MultiUAV2 simulation is a (SIMULINK/MATLAB/C++)-based simulation that is capable of simulating multiple unmanned aerospace vehicles which cooperate to accomplish a predefined mission. The simulation is organized using the MATHWORKS' SIMULINK simulation software, but most of the functionality is in MATLAB script functions. MultiUAV2 is a non-real-time simulation that contains six-degree-of-freedom (6DOF) vehicle dynamics models, simple target models, and user-defined cooperative control algorithms. The nominal simulated scenario consists of searching an area and prosecuting the targets found there. Construction of the simulation satisfied the need for a simulation environment that researchers can use to implement and analyze cooperative control algorithms. The simulation is implemented in a hierarchical manner with inter-vehicle communications explicitly modelled. During construction of MultiUAV2, issues concerning memory usage and functional encapsulation were addressed. MultiUAV2 includes plotting tools and links to an external program for post-simulation analysis. Each of the vehicle simulations include 6DOF dynamics and embedded flight software. The embedded flight software consists of a collection of managers (agents) that control situational awareness and responses of the vehicles. Managers included in the simulation are: Tactical Maneuvering, Sensor, Target, Cooperation, Route, and Weapons.

During the simulation, vehicles fly predefined search trajectories until a target is encountered. Each vehicle has a sensor footprint that defines its field of view. Target positions are either set randomly or they can be specified by the user. When a target position is inside of a vehicle's sensor footprint, that vehicle runs a sensor simulation and sends the results to the other vehicles. With actions based on the selected cooperative control algorithm, the vehicles prosecute the known targets. For the nominal simulation, the vehicles are destroyed when they attack a target. During prosecution of the targets the vehicles generate their own minimum-time trajectories to accomplish tasks. The simulation takes place in a three dimensional environment, but all of the trajectory planning is for a constant altitude, i.e. two dimensions. Once each vehicle has finished its assigned tasks it returns to its predefined search pattern trajectory. The simulation continues until it is stopped or the preset simulation run time has elapsed.

1.2 Implementation

MultiUAV2 is organized into two major top-level blocks, **Vehicles** and **Targets**, see Figures 1.1–1.3. The other two blocks at the top level, **Initialization** and **DataForPlotting**, call functions to initialize

the simulation and save simulation data for plotting. Nominally, the top-level blocks contain the sub-blocks and connections required to implement simulation of 8 vehicles and 10 targets, see Figures 1.2–1.5. Information flow between the vehicles is facilitated with a *communication simulation*, see Chapter 4. Information flow between blocks within each vehicle is implemented using SIMULINK *wires* and, sparingly, global MATLAB memory. To facilitate simulation truth data flow between the objects in the simulation a truth message passing mechanism is used, see Chapter 4.

Nominally there are 8 vehicles and 10 targets implemented in MultiUAV2. By changing global parameters, the number of targets and vehicle used in a simulation can be decreased. The number of vehicles and targets can be increased by adding mode blocks and making changes to global parameters. All of the vehicles in this simulation have the same simulation structure. The same is true for the targets. Therefore, to implement the simulation only one vehicle block and one target block needs to be built and then copies of these blocks can be used to represent the rest of the vehicles and targets. To simplify simulation model modifications, a vehicle and a target block were implemented and then saved in a SIMULINK block library. This Cooperation block library was used to instantiate the Vehicle and Target blocks. When one uses a block from a block library, a link from the block to the library is created so when the library is updated the linked blocks are also updated. Therefore the first vehicle or target block is the *real* block and the rest of the blocks are links to a copy of the *real* blocks in the Cooperation block library.

1.3 Using This Manual

The *Getting Started* and *Modifications To The Simulation* sections of the manual, see Chapters 2 and 6, contain step by step instructions for operating and changing the MultiUAV2 simulation. The sections, *Embedded Flight Software*, chapter 3, *Inter-Vehicle/Simulation Truth Communications*, chapter 4, and, *Vehicle Dynamics Simulation*, chapter 5, contain background information on major functions. References for *M-Functions*, *Global Variables*, and *Global Structures* are located in the appendices, see Appendix A, B, and C.

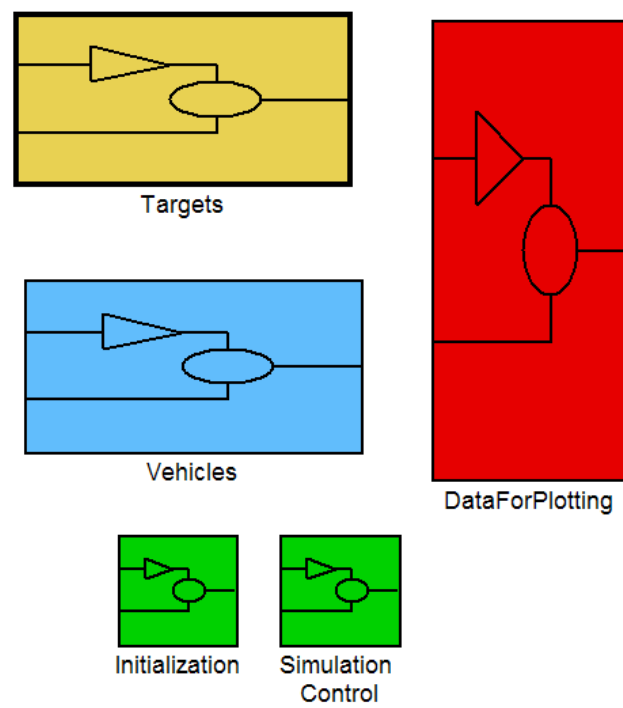


Figure 1.1: Top level block layout.

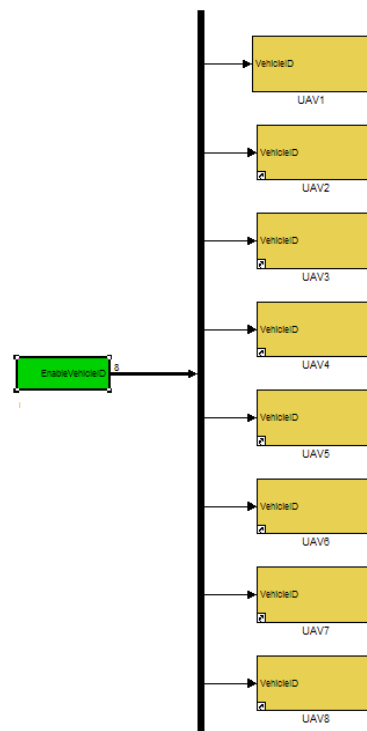


Figure 1.2: Layout of vehicle blocks.

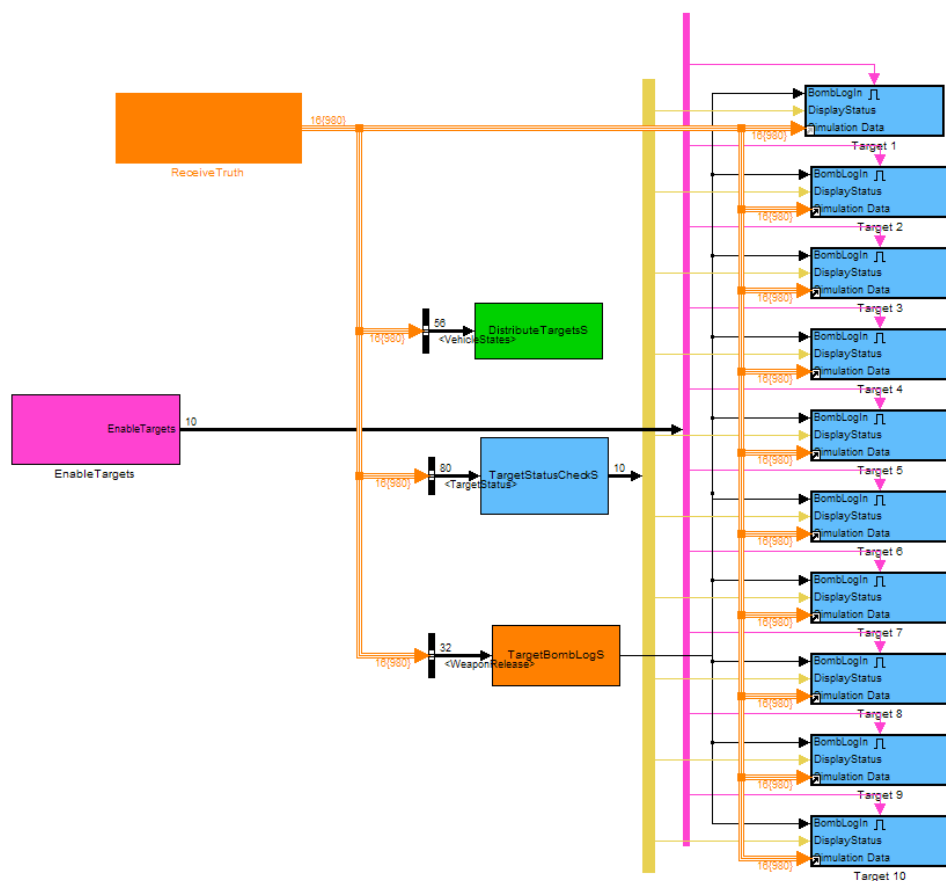


Figure 1.3: Layout of target blocks.

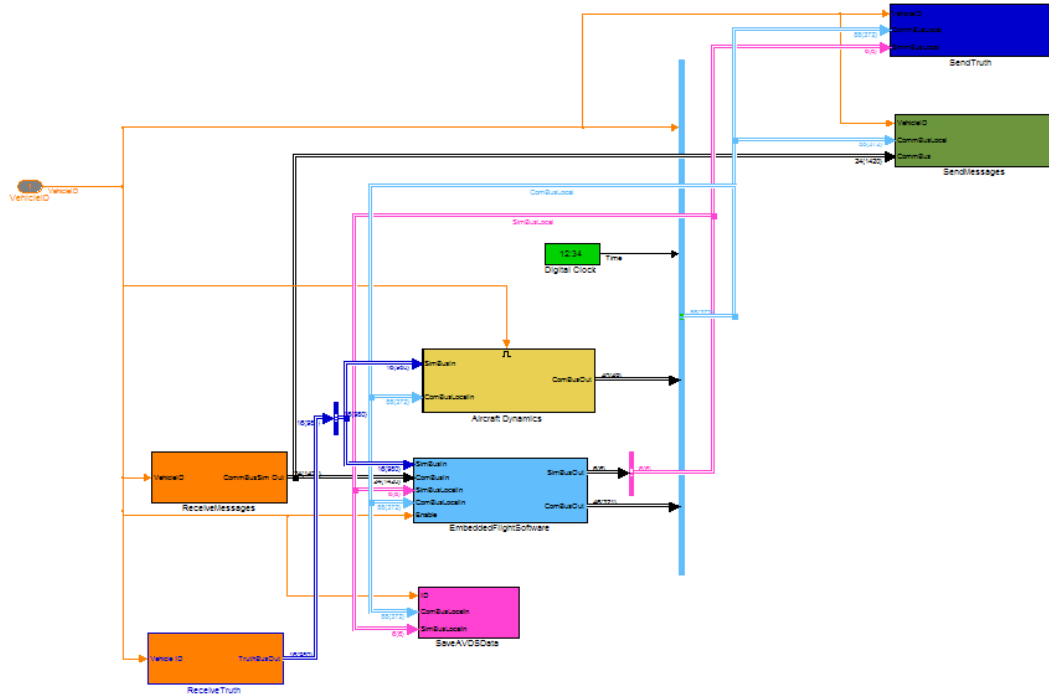


Figure 1.4: Layout of blocks inside the vehicle.

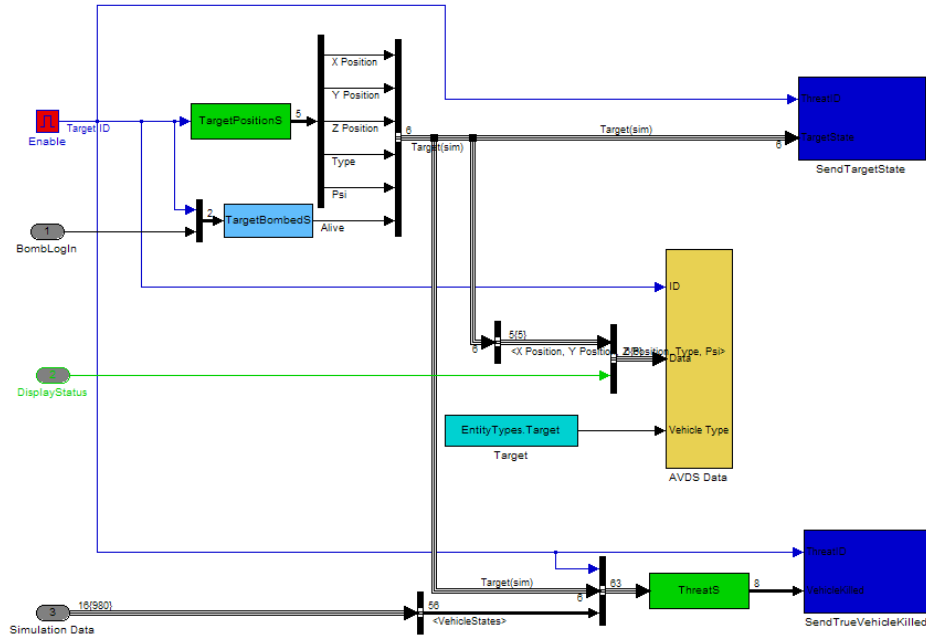


Figure 1.5: Layout of blocks inside the target.

Chapter 2

Getting Started

2.1 Setting-up the Simulation

The files for the MultiUAV2 simulation are in and below the directory **MultiUAV2**, Figure 2.1. If these directories and files are present, no other setup is required. The contents of the **MultiUAV2** directory are:

| | |
|-----------------------|---|
| startup.m | Script to setup the simulation environment. |
| AVDSData | Data directory for AVDS visualization of sim results. |
| Documents | Directory for highest level documentation, i.e. manual, etc. |
| InputFiles | Directory for various input files needed by the simulation. Typically used only by s-function files. |
| m-file | Directory for all of the m-file scripts/functions. |
| MonteCarloData | Data directory for Monte-Carlo simulation data. |
| s-model | Directory for all of the SIMULINK models. |
| src | Directory for compiled and source C++ material for mex-/s-func, and additional libraries; makefile(s) and MSVC++ project files. |
| tool | Directory to hold little tools/scripts mostly useful for development, rather than simulation use. |

2.2 Running the Simulation

To run the simulation, do the following:

1. Start MATLAB in the **MultiUAV2** directory. It will initialize the needed paths, change to the m-file directory, and bring up the graphical user interface (GUI). Alternatively, start MATLAB, change to the **MultiUAV2** directory and run the script **Startup.m**.
2. Many (but not all) simulation parameters are specified in the file: **m-file/InitializeGlobals.m**. There is a GUI button to open this file for editing.
3. Open the SIMULINK model, **MultiUAV.mdl**, by pressing the GUI button marked *Open MultiUAV Main (Simulink)*.
4. Start the Simulation using the SIMULINK controls.

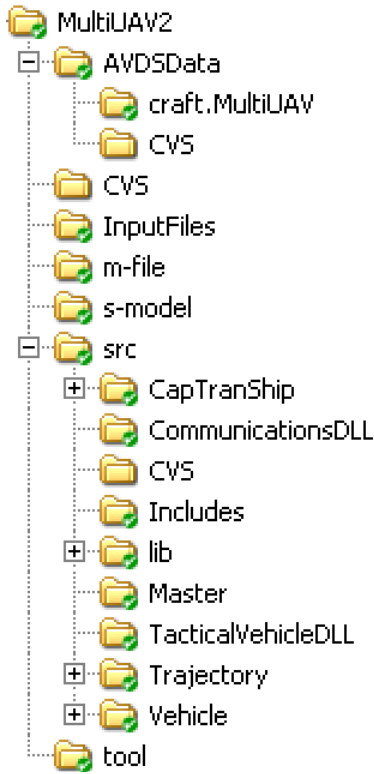


Figure 2.1: MultiUAV2 Directories.

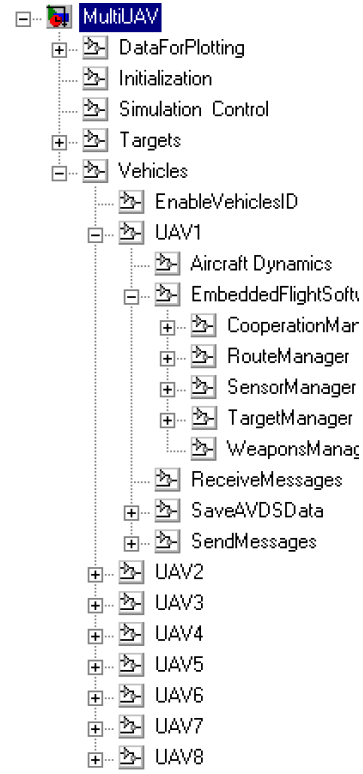


Figure 2.2: MultiUAV2 ModelBrowser.

2.3 The Graphical User Interface (GUI)

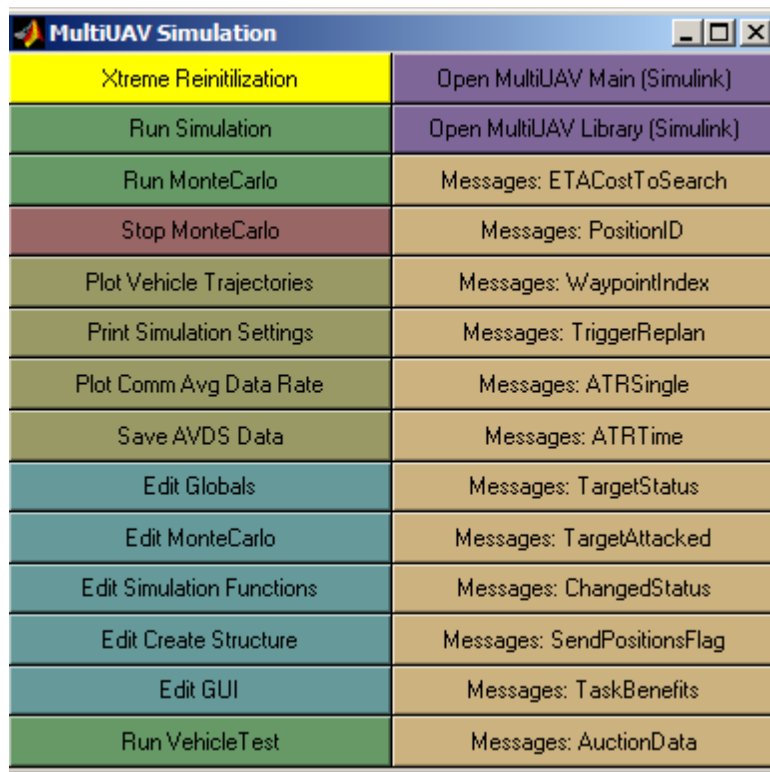
Running the m-file `GUIMultiUAV.m` opens the GUI. Note: `InitializeGlobals` calls `GUIMultiUAV`. The GUI contains buttons, that perform various functions, see Figure 2.3. The functions performed by pressing these buttons are commonly used functions or open commonly used files, see Table 2.1.

To add/remove buttons from the GUI do the following:

1. open the file `GUIMultiUAV.m`.
2. add/subtract a line to the `ButtonsStrings` cell array. Each line has three cells, Button Label, Command string, and Button color string.
3. create a function to handle the command. Note this can be done by adding and new case to the `switch action` function below the definition of the `ButtonStrings`.

2.4 Simulation Output

During the simulation, all vehicle positions, rotations, alive/dead flags, and target assignments are saved for later analysis. The vehicle data is saved to the file, `SimPositionsOut.mat`, in the MATLAB matrix, `XYPositions`, with the columns corresponding to elapsed time and the rows defined as shown in Table 2.2. During the simulation, all target positions and states are saved to the file,



| MultiUAV Simulation | |
|---------------------------|----------------------------------|
| Xtreme Reinitialization | Open MultiUAV Main (Simulink) |
| Run Simulation | Open MultiUAV Library (Simulink) |
| Run MonteCarlo | Messages: ETACostToSearch |
| Stop MonteCarlo | Messages: PositionID |
| Plot Vehicle Trajectories | Messages: WaypointIndex |
| Print Simulation Settings | Messages: TriggerReplan |
| Plot Comm Avg Data Rate | Messages: ATRSingle |
| Save AVDS Data | Messages: ATRTime |
| Edit Globals | Messages: TargetStatus |
| Edit MonteCarlo | Messages: TargetAttacked |
| Edit Simulation Functions | Messages: ChangedStatus |
| Edit Create Structure | Messages: SendPositionsFlag |
| Edit GUI | Messages: TaskBenefits |
| Run VehicleTest | Messages: AuctionData |

Figure 2.3: Graphical User Interface.

`SimTargetsOut.mat`, in the MATLAB matrix, `TargetPositions`, with the columns corresponding to elapsed time and the rows defined as shown in Table 2.3.

2.5 Simulation Data Plot Window

After running the simulation the saved data can be plotted using the `PlotOutput` function. This function can be invoked directly or by pressing the *Plot Results* button on the GUI. The resulting plot, see Figure 2.4, shows a top-down plan-view plot of the simulation data. The plot shows the vehicle positions (numbers), sensor footprints (large colored rectangles), targets (small rectangles), markers (small colored squares near the targets) indicating vehicle to target assignment, and the paths of the vehicles (colored lines). Included on the plot are the following controls:

Graphics Toolbar this is MATLAB's standard toolbar that can used to zoom, print, annotate and save the plot.

Pull-Down Menu Options these menus offer the following options:

Trajectory/Trail selections include:

Trajectory plot the full path at the start of the animation

Trail plot the path behind the moving vehicle

None do not plot the path

Miles/Feet selections include:

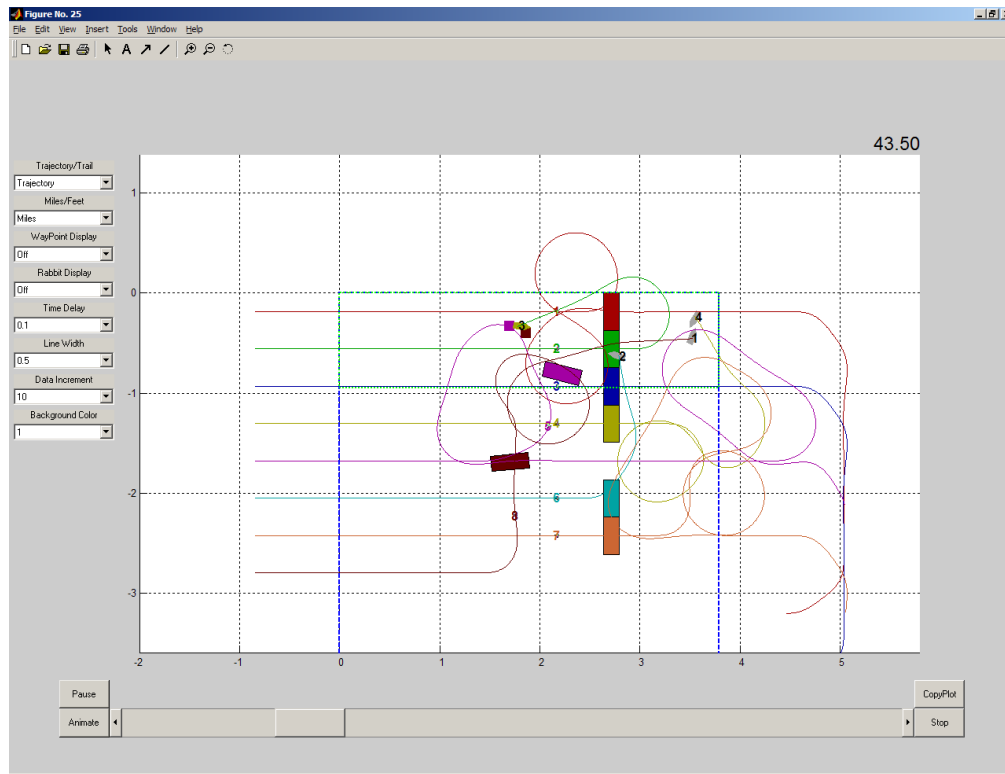


Figure 2.4: MultiUAV2 Plot Window.

Feet use feet for display units

Miles use miles for display units

Waypoint Display show/hide last set of waypoints used by each vehicle

Rabbit Display show/hide the control system rabbit for each vehicle

Time Delay amount of time to delay between plot updates during animation

Line Width width of lines in the plot

Data Increment number of data points to skip between animation updates

Background Color set the background color of the plot

Simulation Time display of simulation time in seconds

Pause Button pause the animation

Animate Button start the animation and redraw the plot

Elapsed-Time Slider position of this slider represents simulation time

Stop Button stop the simulation

Copy Plot Copies the vehicle trajectory plot into a new plot window that does not have the GUI buttons. This is used to generate figures for documentation.

| Button Name | Action |
|----------------------------------|--|
| <i>Run Simulation</i> | starts the MultiUAV2 simulation. |
| <i>Run MonteCarlo</i> | start the Monte-Carlo simulation. |
| <i>Stop MonteCarlo</i> | stops the Monte-Carlo simulation when the current simulation run completes. |
| <i>Plot Simulation Results</i> | opens the Simulation Data Plot window, see Section 2.5. NOTE: <code>OptionSaveDataPlot</code> must be set to one before running the simulation to save data for plotting. |
| <i>Print Simulation Settings</i> | prints the values of the global constants in the MATLAB window. |
| <i>Plot Comm History</i> | opens a plot of the communication history of last simulation. |
| <i>Save AVDS Data</i> | save simulation data for playback in AVDS. NOTE: <code>OptionSaveDataAVDS</code> must be set to one before running the simulation to save AVDS data. |
| <i>Edit Globals</i> | opens the file <code>InitializeGlobals.m</code> for editing. This file is used to set up the global constants for the simulation. |
| <i>Edit MonteCarlo</i> | opens the file <code>MonteCarlo.m</code> for editing. This file is used to set up and run Monte-Carlo simulations. |
| <i>Edit Simulation Functions</i> | opens the file <code>SimulationFunctions.m</code> for editing. This file is used to initialize the simulation. It is the best place to put break points for debugging. |
| <i>Edit Create Structure</i> | opens the file <code>CreateStructure.m</code> for editing. This file is used to create most of the data structures in the simulation. It is a good place to go to find out what elements are defined ofr a particular structure. |
| <i>Run VehicleTest</i> | runs the single vehicle test simulation <code>VehicleTest.mdl</code> . |
| <i>Open MultiUAV2 (Simulink)</i> | opens the MultiUAV2 simulation in SIMULINK. |
| <i>Xtreme Reinitialization</i> | clears all memory, the console, and reinitializes the simulation. |
| <i>Edit GUI</i> | opens the file <code>GUIMultiUAV.m</code> for editing. This makes it easy to add/remove buttons from the user interface window. |
| <i>Message: ...</i> | Each one of these buttons print out the stored messages of the indicated type. |

Table 2.1: GUI buttons and their associated actions.

| Beginning Row Numbers | Saved Data |
|-----------------------|-------------------------------|
| XYPositions(1,:) | simulation time in seconds. |
| XYPositions(2,:) | UAV1 position x -direction. |
| XYPositions(3,:) | UAV1 position y -direction. |
| XYPositions(4,:) | UAV1 heading. |
| XYPositions(5,:) | UAV1 vehicle dead flag. |
| XYPositions(6,:) | UAV1 target assignment. |
| . . . | |
| XYPositions(37,:) | UAV8 position x -direction. |
| XYPositions(38,:) | UAV8 position y -direction. |
| XYPositions(39,:) | UAV8 heading. |
| XYPositions(40,:) | UAV8 vehicle dead flag. |
| XYPositions(41,:) | UAV8 target assignment. |

Table 2.2: Simulation output, vehicle data.

| Beginning Row Numbers | Saved Data |
|-----------------------|-----------------------------------|
| TargetPositions(1,:) | simulation time in seconds. |
| TargetPositions(2,:) | Target1 position x -direction. |
| TargetPositions(3,:) | Target1 position y -direction. |
| TargetPositions(4,:) | Target1 position z -direction. |
| TargetPositions(5,:) | Target1 type. |
| TargetPositions(6,:) | Target1 status (state). |
| TargetPositions(7,:) | Target1 heading. |
| . . . | |
| TargetPositions(56,:) | Target10 position x -direction. |
| TargetPositions(57,:) | Target10 position y -direction. |
| TargetPositions(58,:) | Target10 position z -direction. |
| TargetPositions(59,:) | Target10 type. |
| TargetPositions(60,:) | Target10 status (state). |
| TargetPositions(61,:) | Target10 heading. |

Table 2.3: Simulation output, target data.

Chapter 3

Embedded Flight Software (Managers)

3.1 Overview

The MultiUAV2 simulation contains the Embedded Flight Software (EFS) blocks necessary to implement cooperative control of the vehicles. EFS is a collection of software managers that cause the vehicle to perform the desired tasks, see Figure 3.1. The following managers have been implemented: Tactical Maneuvering, Sensor, Target, Cooperation, Route and Weapons. These managers are described in the following sections.

3.1.1 Redundant Central Optimization

Many of the cooperative control algorithms are implemented in a *Redundant Central Optimization* (RCO) manner to control the cooperation of vehicles while they carry out their mission to find, classify, kill, and verify the targets in the simulation. RCO consists of vehicles that are formed into a team that contains team members and a team agent as shown in Figure 3.2. The team agent makes and coordinates team member assignments through the use of a centralized optimal assignment selection algorithm that is based on partial information. The redundant portion of the RCO structure comes about because each team member implements a local copy of the team agent. Because of this, each of the team members calculates assignments for the entire team and then implements the assignment for itself.

3.1.2 Sequence of Events

During the progress of the simulation the EFS managers cause the vehicle to react to changes in target states, vehicle tasks, and task assignments. As an example of the information flow between EFS managers during the simulation, when the CapTransShip algorithm is selected the following is a sequence of events that occur when a previously undetected target is discovered:

1. Vehicle Dynamics block senses target:
 - Makes vehicle heading and target ID available to local vehicle.
2. The local Sensor Manager calculates single ATR based on information from the Vehicle Dynamics block:

- Makes single ATR available to all vehicles.
- 3. Sensor Managers on all vehicles calculate combined ATR value based on information from all vehicles:
 - Makes combined ATR available to local vehicle.
- 4. Target Managers on all vehicles update the target state based on the combined ATR value from the local vehicle:
 - Makes target state available to all vehicles.If any of the targets change state
- 5. Route Managers on all vehicles calculate optimal route and cost to the target based on its new state:
 - Makes cost to service target available to all of the vehicles.
- 6. Cooperation Managers on all vehicles calculate optimal assignment of vehicles to targets based on the optimal costs:
 - Makes assignment for local vehicle available to the local vehicle.
- 7. Route Managers on all vehicles implement assigned routes:
 - Makes assigned waypoints available to the local vehicle.
- 8. Tactical Maneuvering Managers on all vehicles read assigned waypoints and calculate commands that will cause the autopilot to cause the vehicle to fly to the waypoints:
 - Makes autopilot commands available to the local vehicle.
- 9. Vehicle Dynamics reads autopilot commands and runs vehicle dynamics simulation:
 - Makes vehicle position and heading available to local vehicle.

3.2 Tactical Maneuvering Manager

This manager is used to perform all of the functions necessary for near-term guidance of the vehicle. At this time the Tactical Maneuvering Manager is only being used to generate autopilot commands to cause the vehicle to follow given waypoints. In order to remove timing differences between the Tactical Maneuvering Manager and the vehicle dynamics, the interface to both of these functions was combined in one S-Function in the Aircraft Dynamics block, see Chapter 5. TacticalManeuvering uses the inputs to the block Aircraft Dynamics as well as the global variables: **WaypointFlags** and **WaypointCells** to generate autopilot commands. The array, WaypointFlags, is used as a check to see if the cell for this vehicle in WaypointCells contains new waypoints.

- Manager Responsibilities:
 - Generates autopilot commands to cause the vehicle to follow given waypoints.
- Data Required by this Manager:

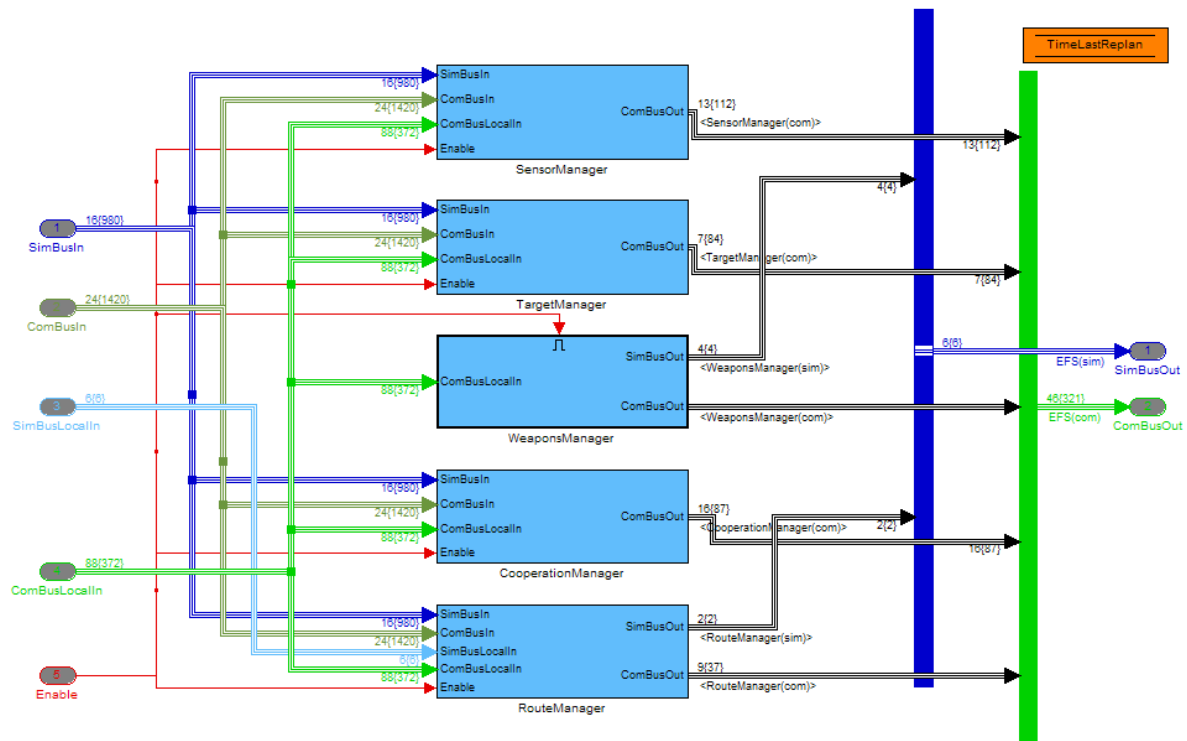


Figure 3.1: MultiUAV2 Managers.

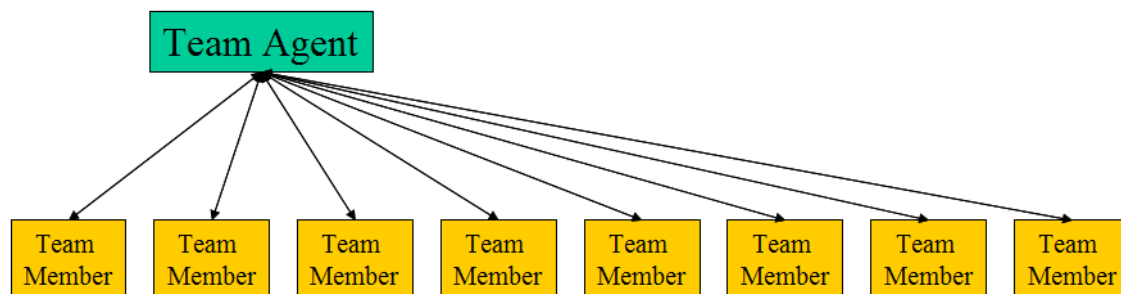


Figure 3.2: UAV team.

- Waypoints to follow
- current state of the vehicle, i.e. position, velocity, etc.
- Data Generated by this Manager:
 - Autopilot commands
 - current waypoint count

3.3 Sensor Manager

This manager is used to perform all of the functions necessary to monitor the sensors and process sensed data.

- Manager Responsibilities:
 - Keeping track of which targets have been detected.
 - Automatic target recognition (ATR) based on sensed data from this vehicle.
 - Combination of ATR values for each target from data communication from this and other vehicles.
 - Calculation of a Battle Damage Assessment (BDA) value, see the ATR Single block.
- Data Required by this Manager:
 - Sensed target value and heading from the current vehicle.
 - Combined ATR values for the other vehicles
- Data Generated by this Manager:
 - Single ATR value
 - Combined ATR value.
 - BDA value
- Description of Functions:

Calculation of single ATR value Given the targets length (L), width (W) and aspect angle¹ (θ) the single ATR value (ATR_s) is calculated with the following equations. A representative plot of ATR_s vs. θ is shown in Figure 3.4.

$$ATR_s = \begin{cases} \frac{W \arccos(\theta) + L \arcsin(\theta)}{L + W} \times SF & \text{for } 0 \leq \theta \leq \frac{\pi}{2} \\ \frac{-W \arccos(\theta) + L \arcsin(\theta)}{L + W} \times SF & \text{for } \frac{\pi}{2} < \theta \leq \pi \\ \frac{-W \arccos(\theta) - L \arcsin(\theta)}{L + W} \times SF & \text{for } \pi < \theta \leq \frac{3\pi}{2} \\ \frac{W \arccos(\theta) - L \arcsin(\theta)}{L + W} \times SF & \text{for } \frac{3\pi}{2} < \theta < 2\pi \end{cases} \quad (3.1a)$$

¹Angle definitions are shown in 3.3.

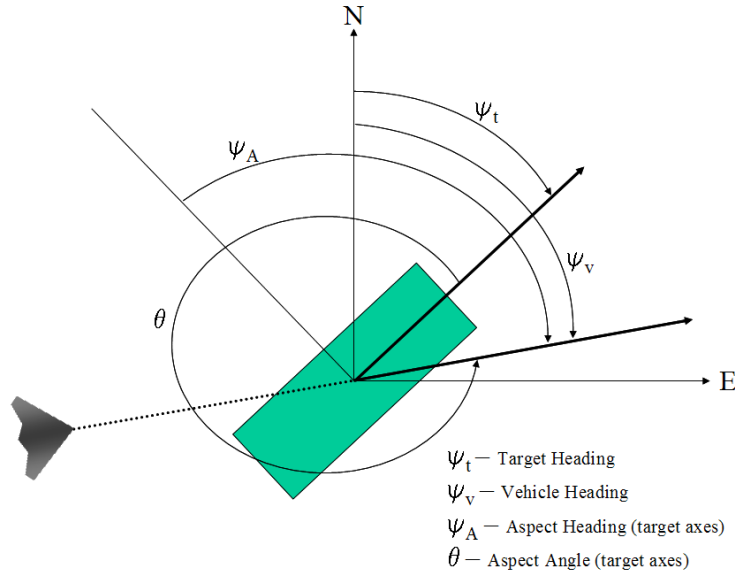


Figure 3.3: Angle definitions for ATR.

$$SF = 0.8 \frac{L + W}{\sqrt{W^2 + L^2}} \quad (3.1b)$$

Calculation of combined ATR value Given the values for ATR_s and the respective angles θ , two single ATR values for a target can be combined into one (ATR_c) with the following equations:

$$ATR_c = (ATR_1 + \rho \times ATR_2) - (ATR_1 \times \rho \times ATR_2) \quad (3.2a)$$

$$\rho = 1.0 - e^{-0.3|\theta_2 - \theta_1|} \quad (3.2b)$$

If more than two single ATR values exist for a target, all combined ATR values are calculated for all combinations of the single values. The largest combined ATR value is used for that target.

Calculation of BDA value At this time there is no calculation for BDA values there is only a check to see if the target is sensed during the time it is ready for BDA.

3.4 Target Manager

Target Manager Creates and manages list of known and potential targets. Creates and manages list of known and potential targets.

- Manager Responsibilities:
 - Perform target classification.
 - Send target information requests based on data needed for high level of confidence in classification.
 - Manage six target states (see Figure 3.5):

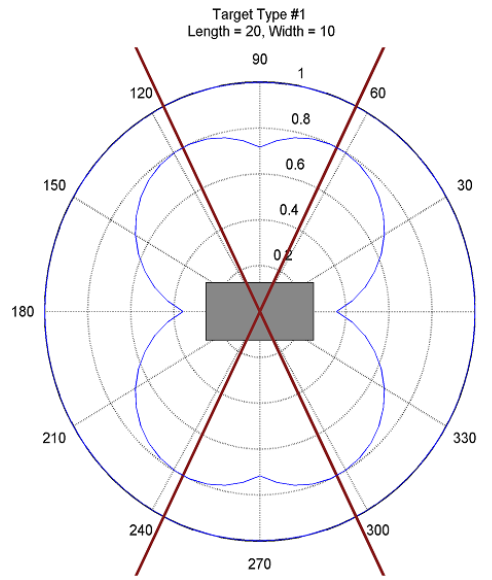


Figure 3.4: ATR template.

\overline{D} Not Detected

D/\overline{C} Detected/Not Classified

C/\overline{A} Classified/Not Attacked

A/\overline{K} Attacked/Not Killed

K/\overline{V} Killed/Not Verified

V Verified

- Account for moving targets and target registration issues.
- Data Required by this Manager:
 - Truth model for any sensed target
 - Angle target was sensed from
 - Sensed target information from other vehicles
- Data Generated by this Manager:
 - New target/Change in targets state
 - State of targets (includes mode, sensed position, ATR values, etc.)
 - Data requirements to feed into the ATR algorithms, i.e. target location, estimated priority, estimated aspect angles,
- Description of Functions:
 - Target State Determination
 - Assume other vehicles target states are correct. Use other vehicle target states to upgrade state this vehicles target states. That is, if any of the other vehicles have a particular target in a higher state, then this vehicle will change that targets state to match.

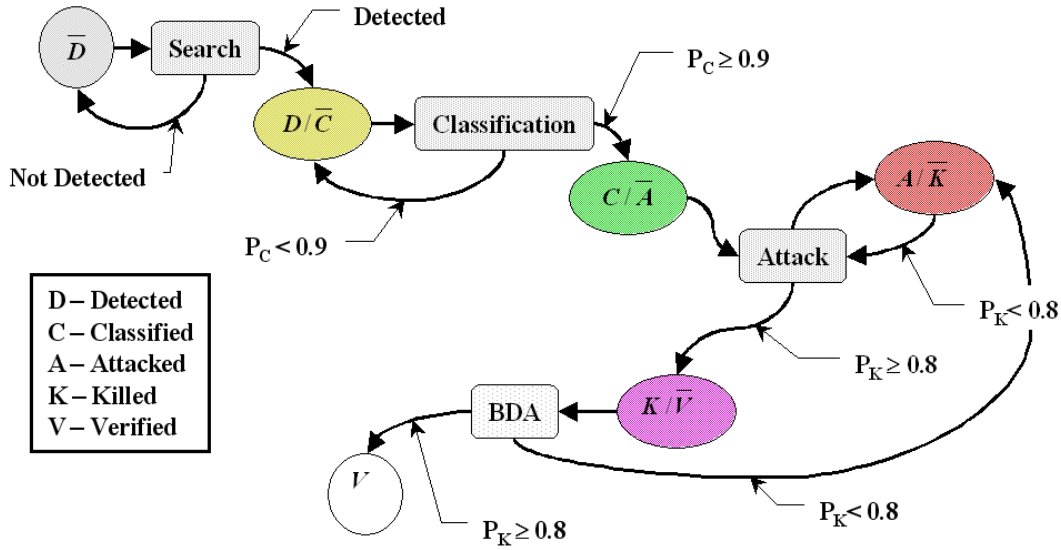


Figure 3.5: Target state transition diagram.

- Implement a state machine to run state transition functions to check to see if the state of a target needs to be changed.
- Output current state for each target. This state implies the action that needs to be taken with respect to the target, i.e Observation, Attack or BDA.

3.5 Cooperation Manager (Assignment Algorithms)

Calculates assignment for the vehicle based on information gathered from all of the vehicles.

- Manager Responsibilities:
 - Perform assignment calculations to assign each vehicle to a task. Tasks include Continue to Search, observation of a potential target, attack of a target, and battle damage assessment of an attacked target.
- Data Required by this Manager:
 - State of each target
 - Benefit of each vehicle performing each available task plus the benefit of each vehicle continuing to search.
- Data Generated by this Manager:
 - Vehicle assignment for each vehicle.

3.5.1 Single Assignment Tour vs Multiple Tour Assignment

A *single task tour* assignment algorithm is an algorithm that assigns each UAV to a target to accomplish one task, i.e. classification, attack or verification. In order to make single assignments

both trajectory planning and assignment algorithms must be considered. While trajectory planning for single assignment tours is not trivial, it is possible to use computational geometry to generate optimal trajectories. During the assignment process, trajectories are generated from all of the UAVs to all of the known targets based on the tasks that need to be accomplished on those targets. For task assignment, a capacitated transshipment algorithm can be used to assign the UAVs to the targets, based on the cost of traversing the candidate paths. Assigning UAVs based on a single tour can be very inefficient, as it doesn't take into account coupling that occurs between performing tasks on targets. That is, when a UAV plans to accomplish a task on a particular target, such as classification, it is much more efficient if that UAV also can take into account the next required task for that target, such as attack. When more than one task is taken into account during the planning and assignment process, the algorithm can be said to be based on *multiple task tours*. The need to include multiple-tours in path-planning and assignment algorithms increases the complexity of these algorithms significantly. This complexity is not only due to the possible combinatorial explosion of possible paths and assignments, but also due to the requirement that the tasks for each target must be accomplished in a specified order. The following sections describe different algorithms that have been implemented for both single and multiple task tour assignments. For more information see Rasmussen et al. [5]

3.5.2 Capacitated Transshipment Network (Network Flow) (Single Task Tours)

A network optimization model is used to calculate the vehicle task assignments. Network optimization models are typically described in terms of supplies and demands for a commodity, nodes which model transfer points, and arcs that interconnect the nodes and along which flow can take place. There are typically many feasible choices for flow along arcs, and costs or values associated with the flows. Arcs can have capacities that limit the flow along them. An optimal solution is the globally least cost (or maximum value) set of flows for which supplies find their way through the network to meet the demands. To model weapon system allocation, we treat the individual vehicles as discrete supplies of single units, tasks being carried out as flows on arcs through the network, and ultimate disposition of the vehicles as demands. Thus, the flows are 0 or 1. We assume that each vehicle operates independently, and makes decisions when new information is received. These decisions are determined by the solution of the network optimization model. For more information on the Network Flow algorithm see Nygard et al. [4], Schumacher et al. [6].

3.5.3 Iterative Network Flow (Multiple Task Tours)

Due to the integrality property, it is not normally possible to simultaneously assign multiple vehicles to a single target, or multiple targets to a single vehicle. However, using the network assignment iteratively, *tours* of multiple assignments can be determined. This is done by solving the initial assignment problem once, and only finalizing the assignment with the shortest estimated time of arrival. The assignment problem can then be updated assuming that assignment is performed, updating target and vehicle states, and running the assignment again. This iteration can be repeated until all of the vehicles have been assigned terminal attack tasks, or until all of the target assignments have been fully distributed. The target assignments are complete when classification, attack, and battle damage assessment tasks have been assigned for all known targets. Assignments must be recomputed if a new target is found or a UAV fails to complete an assigned task. For more information on the Iterative Network Flow algorithm see Schumacher et al. [7].

3.5.4 Iterative Auction (Multiple Task Tours)

Using the same strategy as the Iterative Network Flow, the Iterative Auction builds up multiple task tours of assignments for the vehicles by using a Jacobi auction solver. The auction is used to find an initial set of assignments, freezes the assignment with the shortest estimated time of arrival and then repeats this process until all possible tasks have been assigned. For more information see the explanation of the Iterative Network Flow algorithm in §3.5.3

3.5.5 Relative Benefits (Multiple Task Tours)

This method requires a relaxation of the optimality requirement, but can potentially produce good paths and assignments quickly. One major problem with this and other resource allocation methods is the absence of a good metric to judge its efficacy. There are some possible algorithms that will return results that are very close to optimum, but none of them have been implemented for this type of problem. The central theme of this algorithm is that multiple assignment tours can be developed by making single assignment tours and then trading assignments between the UAVs based on the relative benefit of one UAV taking on the assignment of another. For more information on the Network Flow algorithm see Rasmussen et al. [5].

3.5.6 Distributed Iterative Network Flow (Multiple Task Tours)

The Iterative Network Flow algorithm was initially implemented in a RCO manner, see 3.1.1. For the Distributed Iterative Network Flow, the original Iterative Network Flow algorithms were implemented in a distributed manner, i.e. each vehicle calculates benefits for its self to complete the required tasks at each iteration and then sends these benefits to the other vehicles. All the vehicle run the Network Flow algorithms and then move on to the next iteration.

3.5.7 Distributed Iterative Auction (Multiple Task Tours)

The Iterative Auction algorithm was initially implemented in a RCO manner, see 3.1.1. For the Distributed Iterative Auction, the original Iterative Auction algorithms were implemented in a distributed manner, i.e. each vehicle calculates bids for the required tasks at each iteration and sends these bids to the other vehicles for use in an asynchronous distributed auction.

3.6 Route Manager

This manager is used to plan and select the route for the vehicle to fly. Part of the functionality is calculation of the lowest cost route to all known targets, based on each target's state. The status of the vehicle's assigned task is also calculated. For assignment algorithms that find multiple-task tours, many of the functions of the Route Manager are implemented in the Cooperation Manager.

- Manager Responsibilities:
 - Maintain arrays of waypoints that describe primary and alternate flight trajectories for the vehicle.
 - Calculate new flight trajectories for the vehicle based on mission requirements.
 - Output parameters describing costs of using alternative flight trajectories.

- Data Required by this Manager:
 - Position and ingress headings to all known objects/targets.
 - Current vehicle position and heading.
- Data Generated by this Manager:
 - Cost of each of the alternative flight trajectories.
- Description of Functions:
 - Replan - Uses simple geometry to calculate flight trajectory from vehicles current position and heading to object/target with a specified standoff along a specified ingress heading.
 - Outputs waypoints that are calculated based on a specified turn radius.
 - Waypoints for each alternative flight trajectory are save in a Matlab cell array.

Calculates the ETA, cost and waypoint trajectory for the lowest cost flyable path to each of the targets, to accomplish the appropriate task, and stores the data for later use. The **ReplanRoutes** block calls the M-function, **ReplanRoutes** to do the calculations. The lowest cost set of waypoints for each known target is stored in the appropriate location in the global structure **VehicleMemory.RouteManager**. The function, **MinimumDistance**, is used to calculate the minimum time route from the vehicle's current position to a target given the vehicle's position, velocity vector, commanded turn radius, the desired ingress heading to the target, and the required sensor standoff distance, see Figure 3.6. To do this, **MinimumDistance** uses the following steps:

1. Calculates the centers, O_{v1} and O_{v2} , of the turn circles that are connected to the vehicle using the vehicle's position, velocity and commanded turn radius.
2. Calculates the point SO, based on T, desired heading and standoff distance.
3. Uses SO, T and the commanded turn radius to calculate the centers of the turn circles O_{t1} and O_{t2} .
4. Determines the relative turn directions for both O_{t1} and O_{t2} (clockwise/counterclockwise).
Note: At this point there are two circles tangent to the vehicle and two turn circles tangent to the line between SO and T at SO. The trajectories for all of the combinations of vehicle turn circles and standoff turn circles are calculated and the trajectory that produces the shortest time to the target is considered the optimum trajectory. The following steps are used to calculate each trajectory (calculations for the circles O_{v2} and O_{t1} are shown for convenience).
5. The coordinates of all of the points are transformed to the coordinate system where the center of the vehicle turn circle (O_{v2}) is at the origin and the x-axis is along the line that intersects the O_{v2} and the standoff turn circle (O_{t1}).
6. Based on the relative turn directions of the two circles, tangent points for a line tangent to both turn circles are calculated. Because of the turn directions there is only one trajectory, tangent to both circles, that vehicle will be able to use to fly to the target. If the turn directions are the same sign, i.e. both clockwise, then the tangent line will be parallel to the transformed x-axis. If the turn directions are opposite, as in the example, the tangent line, line $T_{v2} - T_{t1}$, will be transverse between the circles.

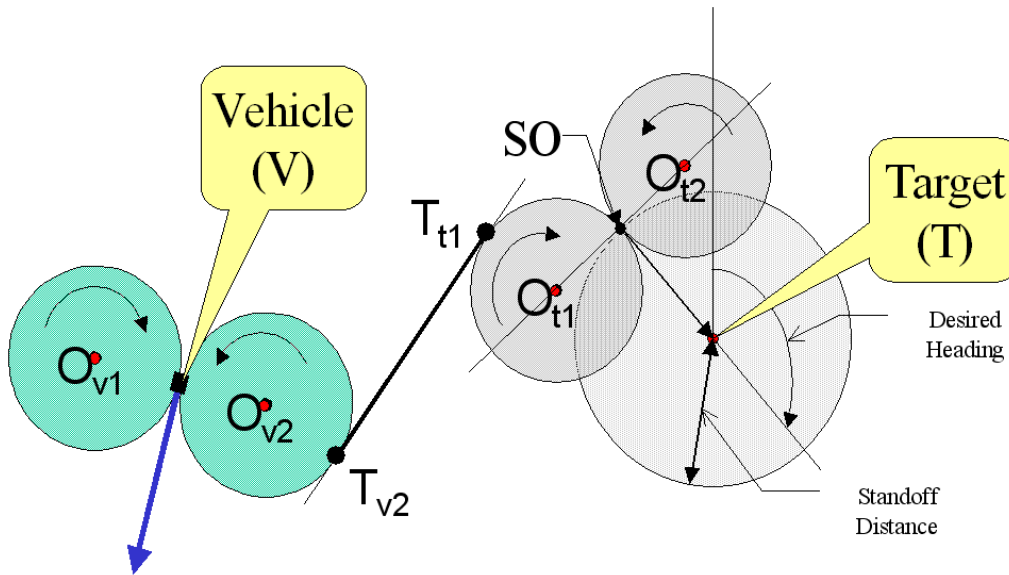


Figure 3.6: Geometry for trajectory calculation.

7. The coordinates of the tangent points are transformed back to the original coordinates system.
8. Finally, the length of this trajectory is calculated for comparison with trajectories from the other turn circle combinations.

3.7 Weapons Manager

Weapons Manager Selects a weapon and then simulates its deployment. Calls the function `Weapon-sRelease.m` which returns a unique `BombID` number, the type of bomb dropped and the bomb's impact coordinates.

Chapter 4

Inter-Vehicle/Simulation Truth Communications

4.1 Overview

The MultiUAV2 simulation has two mechanisms for passing messages between objects in the simulation, one for communication messages and one for simulation truth messages. Previous releases of the MultiUAV2 simulation provided vehicle-to-vehicle communication via a signal bus denoted by **CommBus**, while a second aggregated signal bus, labeled **SimBus**, contained the *truth* information for the simulation. The combination of these two data buses represented the complete information state of the simulation. This *perfect* information state was available to all vehicles at every simulation time-step. From many perspectives, perfect information access is unacceptable, particularly when considering communication and processing delays. Thus, to incorporate communication and processing delays into MultiUAV2, a new communication framework was introduced, see Figure 4.1. In order to make it possible to distribute the MultiUAV2 over many computers, a similar framework was introduced for passing truth information between objects in the simulation.

4.2 Communication Requirements

Maximum design flexibility is a significant and yet vague requirement that must be met by any potential communication design. By maintaining genericity, we ensure that the resulting solution will accommodate the simulation of specific communication requirements, e.g. protocol-specific, theater-specific, or hardware-specific, while providing a simple and general framework to quantify vehicle-to-vehicle communication needs, e.g. peak or average data-rate.

To provide flexibility in implementation of communication simulations that contain varying levels of detail, a generic message passing scheme was chosen as the Virtual Communication Representation (VCR). In this design, specific message types and their format are defined centrally in the VCR and made globally available to the various Embedded Flight Software Managers (EFSMs) as context requires¹. Minimally, a message definition must contain a unique message identifier, time-stamp(s), message layout enumeration, and data field to be written by the EFSM context. Particular messages may be selected by the EFSM context as output resulting from a computation that must be remotely communicated. Outgoing messages, which include data, from each vehicle

¹The message structure discussed here refers to the format dictated by the MultiUAV2 package, rather than to messages related to a specific communication system model.

are stored centrally, and pointers to these messages are distributed to an individual input queue for each vehicle. These pointers are composed of the original message header and should minimally inform the receiver of the message type, time sent, quality or priority of the message, and which central repository contains the associated message data. A user defined rule component controls the distribution of incoming messages to all vehicles based on the message headers.

We avoid adhering to a specific communication model in MultiUAV2 by isolating the message delivery rules in user controlled components. Thus, end-users are free to choose any preferred communication model. Moreover, the genericity of the VCR specification provides for easy extension. For more information on the communications design see Mitchell et al. [1, 2], Mitchell and Sparks [3]

4.3 Implementation

Since the MultiUAV2 simulation is implemented as a combination of MATLAB and SIMULINK using m-files and s-functions written in C++ and MATLAB script, it is most convenient to use these existing tools. In the parlance of MultiUAV2, the design abstraction outlined in § 4.2 is encompassed in a communications manager that is divided into separate send and receive blocks contained within the vehicle model.

The autologically named SIMULINK blocks that manage simulation, **SendMessage**, **RecieveCom-**
munications, **SendTruth**, and **RecieveTruth** can be see in Figures 4.2, 4.3, 4.4, and 4.5. Two global MATLAB structures are used to organize and store data for message passing, **g_Communication-**
Memory and **g_TruthMemory**. **g_CommunicationMemory** is used for communication messages and **g_TruthMemory** is used for simulation truth messages. The required entries for both structures are identical, i.e.:

```
NewStructure = struct( ...
    'InBoxes', [], ...
    'Messages', [], ...
    'DelayMatrix', zeros(MaxNumberVehicles), ...
    'NumberMessages', 0, ...
    'MemoryAllocationMetric', [], ...
    'InBoxAllocationMetric', [], ...
    'MsgIndicies', [], ...
    'Transport', CreateStructure('MSG_TransportType') ...
);
```

The following is a list of the required entries for both of the message structures:

InBoxes Storage for the in-boxes. There must an in-box for each object using the message structure.

Messages Storage for message structures.

DelayMatrix A matrix of times that represent communication delays from each object to every other object in the simulation including the delay from one object to itself.

NumberMessages Total number of messages in the **Messages** storage.

MemoryAllocationMetric Keeps track of number of time memory is allocated for messages.

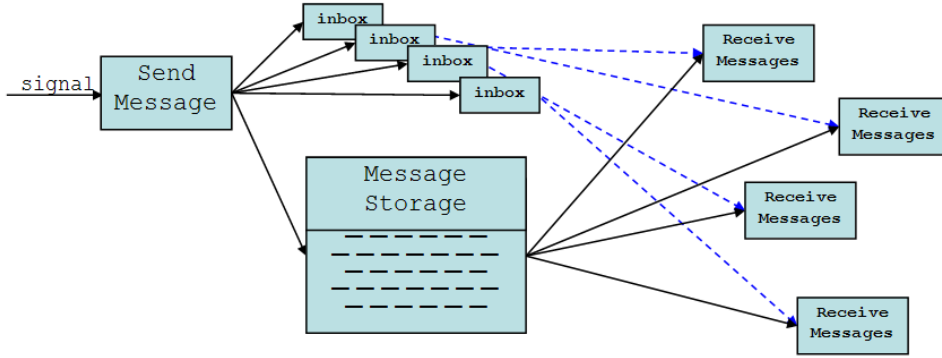


Figure 4.1: Overview of the message passing mechanisms.

| | | | |
|-------------------|----------------------|-----------------|------------------|
| 1:ETACostToSearch | 2:PositionID | 3:WaypointIndex | 4:TriggerReplan |
| 5:ATRSingle | 6:ATRTime | 7:TargetStatus | 8:TargetAttacked |
| 9:ChangedStatus | 10:SendPositionsFlag | 11:TaskBenefits | 12:AuctionData |

Table 4.1: Communication messages and their unique identifiers.

InBoxAllocationMetric Keeps track of number of time memory is allocated for in-boxes.

MsgIndicies Enumerations of the messages, see Tables 4.1 and 4.2

Transport This is storage for a structure that manages how the messages are delivered, i.e through MATLAB global memory or externally.

For more information on message structures see Appendices C.9 and C.10.

4.3.1 Sending Messages

From Figures 4.6 and 4.7, we see the currently specified remote message lists, which are composed of the uniquely enumerated messages seen in Tables 4.1 and 4.2. These messages are defined in and created by calling the m-file script `CreateScturcture.m`. Defining messages in this framework is straightforward and is clearly illustrated by consider a sample message.

The **ATRSingle** signal is generated when the **SensorManager** detects a target and produces an ATR observation. The signal itself contains the time the ATR observation was made and the ATR values for all targets currently known by the observing vehicle. Additional signal data, again for currently known targets, are the vehicle headings for each ATR value, estimated target pose angle, and estimated target type. The corresponding message is generated by aggregating the vehicle identifier, time the message was generated, and the number of entries in the data signal. Thus, the

| | | |
|------------------------|-----------------|----------------------------|
| 1:VehicleState | 2:VehicleIsDead | 3:ChangeVehicleStatus |
| 4:WeaponsRelease | 5:TargetStatus | 6:TargetState |
| 7:VehicleStateSaveData | 8:TrackList | 9:ChangeAssignmentFlagSelf |

Table 4.2: Truth messages and their unique identifiers.

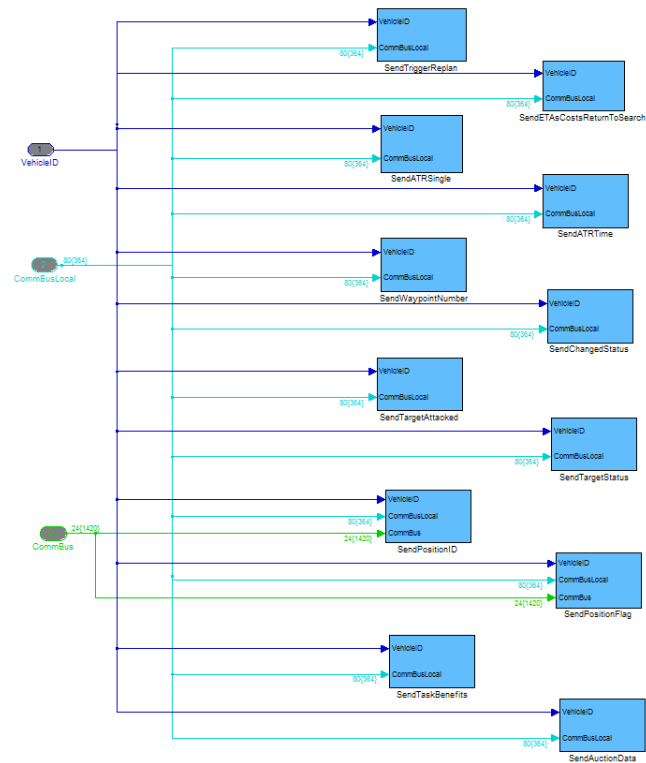


Figure 4.2: Blocks used by the vehicles to send communication messages.

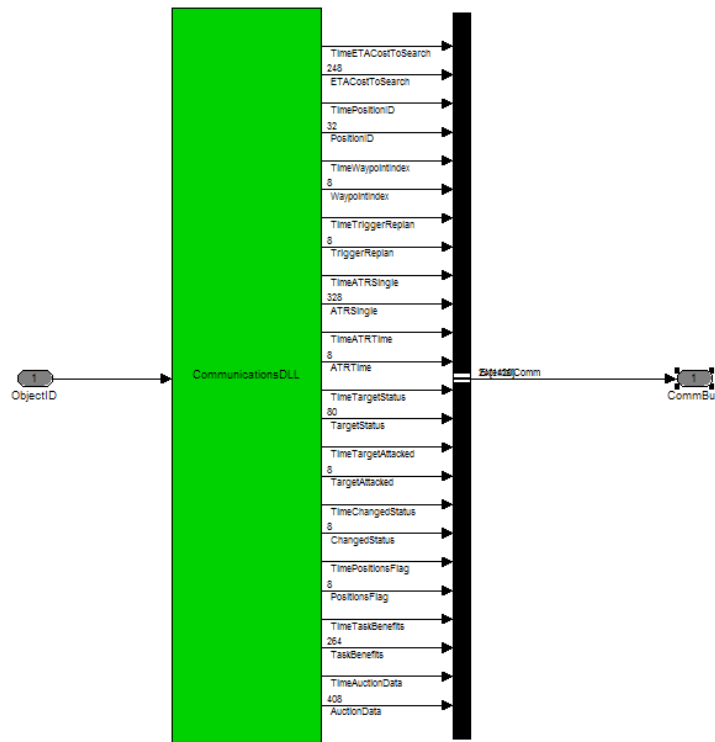


Figure 4.3: Block used to receive communication messages.

ATRSingle message is defined as

```
case 'MSG_ATRSingle'
    NewStructure = struct( ...
        'Title','ATRSingle',...
        'ID',0, ...
        'Enabled',1, ...
        'NumberSenders',MaxNumberVehicles, ...
        'Data',{[]}, ...
        ... %%%%%%%%% Message Storage Enumeration %%%%%%%%%
        'IndexStorageID',[1], ...
        'IndexStorageTimeStamp',[2], ...
        ... %%%%%%%%% Message Content Enumeration %%%%%%%%%
        'VehicleID',[1], ...
        'IndexSinglATR',[2:(1+MaxNumberTargets)], ...
        'IndexSensedHeading',[(2+MaxNumberTargets):(1+2*MaxNumberTargets)], ...
        'IndexEstimatedPoseAngle',[(2+2*MaxNumberTargets):(1+3*MaxNumberTargets)], ...
        'IndexEstimatedType',[(2+3*MaxNumberTargets):(1+4*MaxNumberTargets)], ...
        'NumberEntries',(1+4*MaxNumberTargets), ...
        'SizeToPreAllocate',(AllocationsPer100Sec*2*g_ActiveVehicles), ...
        'TotalNumberMessagesAllocated',0, ...
        'LastMessageIndex',0, ...
        'DefaultMessage',[], ...
```

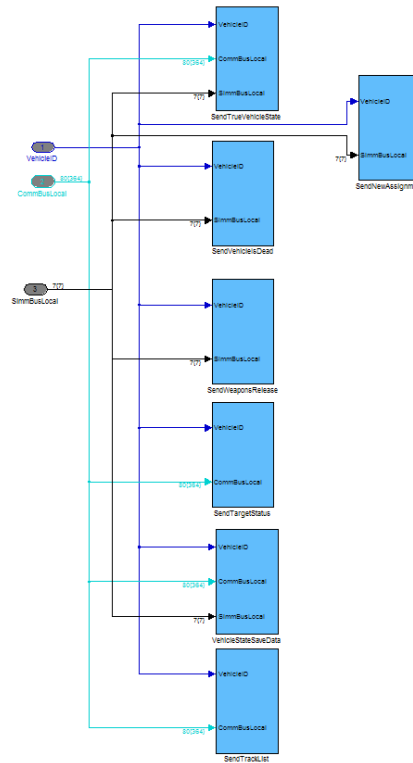


Figure 4.4: Blocks used by the vehicles to send simulation truth messages.

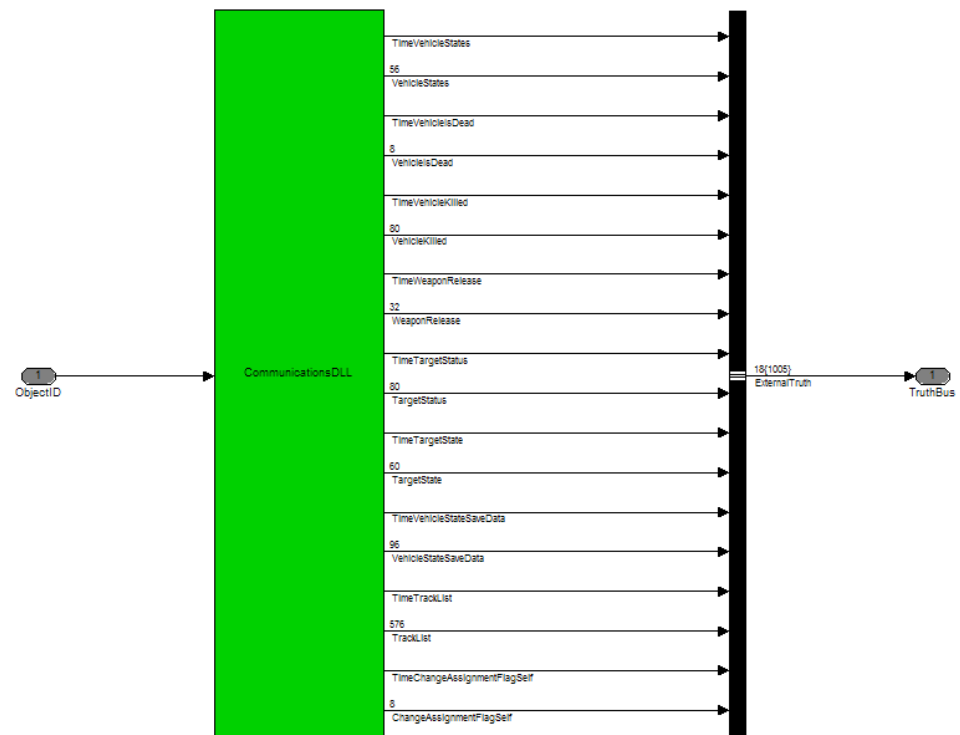


Figure 4.5: Block used to receive simulation truth messages.

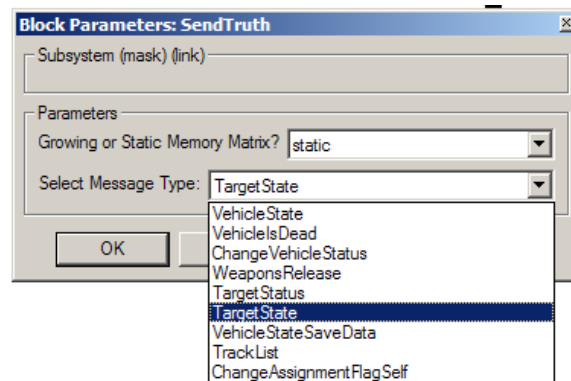


Figure 4.6: Parameter selection for send truth messages block.

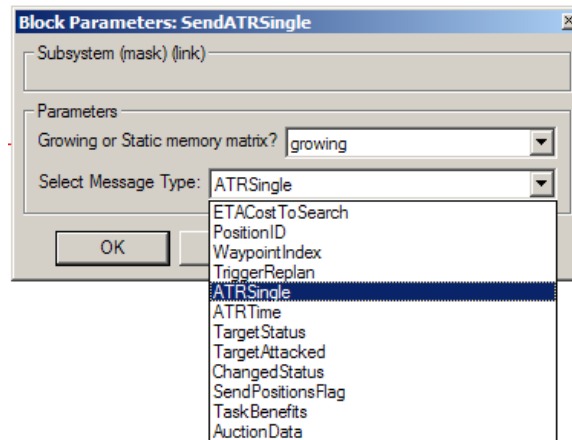


Figure 4.7: Parameter selection for send communication messages block.

```
'MessageDelay',0 ...
);
```

where the constant value `MaxNumberTargets` is autological. In the message definition, the fields are defined as follows:

| | |
|-------------------------------------|---|
| Title | The message title of the corresponding signal name. |
| ID | Unique identifier for the message type. a zero indicates that the ID is uninitialized. |
| NumberSenders | Number of object in the simulation that can send this message. This is used to size the output ports on the receive blocks. |
| Data | This is where the message data is stored. |
| IndexStorageID | The index of the ID entry. Used when working with the Data matrix. |
| IndexStorageTimeStamp | The index of the time that the message was sent. Used when working with the Data matrix. |
| Index... | The indices of the data elements of the message. Used after message has been received. |
| NumberEntries | Total number of data element indices. |
| SizeToPreAllocate | Size of matrix to preallocate/grow a growing matrix. Ideally this number is equal to the required size of the Data matrix at the end of the simulation run. Choosing a number too small cause memory to be allocated more often, slowing down the simulation. Choosing a number too large wastes memory. |
| TotalNumberMessagesAllocated | Used to track amount of memory allocated. |
| LastMessageIndex | Used to track message index number of addressing as well as memory allocation. |
| DefaultMessage | Not used at this time. |

| Field Name | Default Value |
|-----------------------|---------------|
| MessageHeaders | [] |
| IndexTimeStamp | [1] |
| IndexTimeActivate | [2] |
| IndexMessageID | [3] |
| IndexMessagePointer | [4] |
| IndexMessageEvaluated | [5] |
| NumberEntries | (6) |

Table 4.3: InBoxes field description.

MessageDelay Amount of time to add to the message delivery delay for all messages of this type.

During a simulation, messages are accumulated in individual message queues, i.e. the **Data** element of the message structure, that are stored in the **Messages** structure array in the communication/truth message structure. Separate message headers are distributed to the input queues, i.e. **InBoxes**, of the vehicles pointing to the specific message. The message headers that appear in an input queue for each vehicle, are stored in the communication/truth structure under the **InBoxes** structure array identifier, containing the fields with default values seen in Table 4.3. Both the communication, **g_CommunicationMemory**, and truth, **g_TruthMemory**, structures contain storage for in-boxes. Pointers in the in-boxes can only refer to messages that are a part of the main message structure that they are a part of, i.e. **g_CommunicationMemory** or **g_TruthMemory**.

As an example scenario, let **vehicle:1** generate the first simulation **ATRSingle** message at time $t = 30$ s. At $t = 30.50$ s, the message will be processed and available to **vehicle:2**, thus $\Delta t = 0.5$ s. Then, the message header entry contains

$$[30.00 \quad 30.50 \quad 5.00 \quad 1.00 \quad 0.00],$$

and is stored as a single column in **g_CommunicationMemory.InBoxes(2).MessageHeaders**. Reading from left-to-right above, the header indicates that the message arrived at $t = 30$ s, should not be known to **vehicle:2** until $t = 30.5$ s, and is of type **5:ATRSingle**. The next field is the index pointer into the **ATRSingle** message queue. Thus, the message data is accessed through **g_CommunicationMemory.Messages5.Data(:,1)**. The last field in the **MessageHeaders** indicates the process status of the message. Currently, a value of zero (0) indicates the message has not been evaluated while one (1) indicates a processed status. This mechanism for representing message status could also be used to implement a quality of service or priority message structure.

4.3.2 Receiving Messages

The **Receive Messages** blocks, seen in Figure 4.3 and 4.5, represent the SIMULINK interface to the end-user component that specifies how messages should be delivered. This block is an s-function that reads the current vehicle's message queue via **mex** access at every major model update, processes messages, and constructs an output list of signals to be fed by to the SIMULINK simulation. The individual signals are aggregated onto a bus denoted by **ExternalComm** where they can be retrieved as needed by the vehicle simulations. For algorithm specifics, the s-function associated with the **CommunicationsDLL** block is defined in the C++ file **CommunicationsDLL.cpp** located

in the `MultiUAVDLLs/CommunicationsDLL` directory. The required parameter for the `CommunicationsDLL` block is the name of the message structure to use, i.e. either `g_CommunicationMemory` or `g_TruthMemory`.

4.4 Message Exchange Example

When one simulation object sends a message to another simulation object the following events occur:

1. The simulation object changes the time stamp of the message in the appropriate `Send Message` block. (SIMULINK)
2. The changed time stamp causes the `Send Message` block to call the MATLAB function, `SendMessageS`. (SIMULINK)
3. `SendMessageS` appends the data for the message to the end the appropriate `.Data` matrix for the message, i.e. for `ATRSingle` the data matrix is `g_CommunicationMemory.Messages5.Data(:,1)`. (MATLAB)
4. For communication messages, `SendMessageS` calculates delivery times for the message for each of the messages based on the global matrix, `g_CommunicationMemory.DelayMatrix`. (MATLAB)
5. `SendMessageS` appends entries to the `InBoxes` of the intended message receivers. This includes setting the `IndexMessageEvaluated` flag equal to zero. (MATLAB)
6. At each model update, each of the simulation object's `Receive Message` blocks are evaluated and they call the s-function `CommunicationsDLL`. (SIMULINK)
7. The `CommunicationsDLL` function retrieves the simulation object's `InBoxes` and checks the `IndexMessageEvaluated` flags for unevaluated messages, i.e. those with a zero value. (C++)
8. If unevaluated messages are found, their delivery time is checked against the simulation time. If the delivery time is less than the simulation time, the message is inserted into the appropriate output of the `Receive Message` block. (C++)
9. The time stamp output, of the `Receive Message` block, for the appropriate message type is updated to signal a new message. (C++)

Chapter 5

Vehicle Dynamics Simulation

5.1 Overview

Vehicle dynamics, sensor footprint, and tactical maneuvering manager are aggregated in a single s-function, `TacticalVehicleDLL`. For more information on the `Tactical Maneuvering Manager`, see § 3.2. The vehicle dynamics are based on inputs from a file of aerodynamic forces, moments, and damping derivatives. The aerodynamic parameters are used, along with physical parameters, in a nonlinear six-degree-of-freedom equations of motion simulation to generate the vehicle dynamics, see § 5.3. The sensor footprint is implemented as a fixed area that is positioned relative to the vehicle. Using supplied true positions of targets, the sensor footprint algorithm reports any targets that are inside the sensor footprint area, see § 5.4.

5.2 Tactical Vehicle

`TacticalVehicleDLL` is an S-function that aggregates vehicle dynamics simulation with the `Tactical Maneuvering Manager`, and the sensor footprint simulation. This S-function calls the `TacticalVehicle` update function every major model update. The `TacticalVehicle` update function executes the vehicle model, tactical maneuvering manager, and sensor footprint at 100 Hz. There are three sources for inputs to the `TacticalVehicleDLL` s-function, block parameters, block inputs, and global memory. The block parameters, see Table 5.1, are used to setup constants to configure the function. The s-function block inputs are used for simulation generated signals that do not change dimension during the simulation, see Table 5.2. MATLAB global memory is mainly used for information generated during the simulation that changes dimensions, i.e. waypoints, see Table 5.3. See Table 5.4 for a list of the outputs from the `TacticalVehicleDLL` s-function. The vehicle state is initialized using entries in the structure, `VehicleMemory(-).Dynamics`. The elements of this structure are:

```
VTrueFPSInit: 370
PsiDegInit: 0
PositionXFeetInit: -4.593175853000000e+003
PositionYFeetInit: -9.842519685000001e+002
PositionZFeetInit: 675
NumberBombsInit: 1
FuelLB: 15000
```

During the simulation the vehicles use waypoints, contained in the array of cell arrays `WaypointCells`, for navigation. Each vehicle is assigned a waypoint cell array and these waypoint cells are stored in the `WaypointCells` array. The array `WaypointFlags` is used to force `TacticalVehicleDLL` to reread the waypoint cells, i.e. to change the vehicle's waypoints, change the waypoint cell and set the vehicle's `WaypointFlag` equal to 1. Initial search waypoints are generated in the MATLAB function `CalculateWaypoints`.

| | |
|------------------------------------|---|
| <code>StandAloneFlag</code> | This flag is set to zero for this application. |
| <code>NumberTargets</code> | The maximum number of targets in the simulation |
| <code>SensorRollTolerance</code> | Maximum roll angle, in degrees, for sensor operation. |
| <code>WaypointNumberEntries</code> | Number of entries per waypoint. |

Table 5.1: Parameters to the `TacticalVehicleDLL` S-function.

| | |
|--|---|
| <code>VehicleID</code> | Vehicle ID index |
| <code>CmdTurnRadius</code> | Commanded turn radius (feet) |
| <code>Target(1).Position</code> | x, y, z position of target 1 (feet) |
| <code>Target(1).Type</code> | type of target 1 |
| <code>Target(1).Heading</code> | heading of target 1 (deg) |
| <code>Target(1).Alive</code> | Alive flag for target 1 |
| ... | ... |
| <code>Target(MaxNumberTargets).Position</code> | x, y, z position of target <code>MaxNumberTargets</code> (feet) |
| <code>Target(MaxNumberTargets).Type</code> | type of target <code>MaxNumberTargets</code> |
| <code>Target(MaxNumberTargets).Heading</code> | heading of target <code>MaxNumberTargets</code> (deg) |
| <code>Target(MaxNumberTargets).Alive</code> | Alive flag for target <code>MaxNumberTargets</code> |

Table 5.2: Simulink inputs to the `TacticalVehicleDLL` S-function.

| | |
|---------------------------------------|--|
| <code>WaypointFlags</code> | Array of flags to trigger reloading waypoints. |
| <code>WaypointCells</code> | Cell array of waypoints. |
| <code>WaypointStartingIndex</code> | Array of waypoint starting indices. |
| <code>VehicleMemory().Dynamics</code> | Vehicle initialization parameters. |

Table 5.3: MATLAB inputs to the `TacticalVehicleDLL` S-function.

5.3 Variable Configuration Vehicle Simulation

Vehicle dynamics in MultiUAV2 are generated using a simulation called *Variable Configuration Vehicle Simulation* (VCVS). VCVS is a nonlinear six-degree-of-freedom vehicle simulation that includes a control system which reconfigures the simulation for new aerodynamic and physical vehicle descriptions. Vehicle dynamics are based on two configuration files, one containing aerodynamic data and the other physical and control system parameters. The aerodynamic configuration file contains tables of non-dimensional forces, moments, and damping derivatives. The vehicle model calculates aerodynamic forces and moments by using the vehicle's state and control deflections as independent variables to look-up values from the aerodynamic tables. During the look-up process, linear

| | |
|-----------------------------------|---|
| Position_x, Position_y, Altitude | vehicle position in feet |
| V_true_kts | true velocity in knots |
| V_true_fps | true velocity in feet per second |
| Phi, Theta, Psi | angular orientation in degrees |
| Alpha, Beta | angle of attack and sideslip angle in degrees |
| Mach | Mach number |
| VNorth | North velocity in feet per seconds |
| VEast | East velocity in feet per seconds |
| VDown | Down velocity in feet per seconds |
| PsiFiltered | Filtered vehicle heading, filter not used |
| Thrust | Thrust in pounds (not used) |
| SensorOn | is the sensor on, based on the roll angle |
| CommandHeading | Commanded heading in degrees |
| CommandAltitude | Commanded altitude in feet |
| CommandVelocity | commanded velocity in feet per second |
| WayPointNumber | The current waypoint the vehicle is travelling toward |
| WayPointTypeCurrent | type of the current waypoint |
| WayPointTypeLast | type of the last waypoint |
| WayPointTargetHandleCurrent | ID of the next target assigned |
| WayPointTargetHandleLast | ID of the last target assigned |
| RabbitNpos, RabbitEpos, RabbitHdg | state of the trajectory reference |
| TotalSearchTimeSeconds | total search time in seconds |
| AssignedTarget | ID of currently assigned target |
| AssignedTask | type of currently assigned task |
| SensedTargets(MaxNumberTargets) | IDs of targets that were found in the sensorfootprint |

Table 5.4: Outputs from the `TacticalVehicleDLL` S-function.

interpolation is used for states and deflections not found in the tables. The non-dimensional values obtain from the tables are combined with vehicle state data to calculate forces and moments acting on the center of gravity of the vehicle. These forces and moments are combined with external forces and moments, i.e forces and moments from an engine. The forces and moments are used, along with the physical parameters, to calculate the equations of motion. Included in the model are first-order actuator dynamics, including rate and position limits, and first-order engine dynamics.

V CVS uses a dynamic inversion control system with control allocation as its inner loop control system, see Figure 5.1. A rate control system was wrapped around the inner loop to move from angular acceleration commands to angular rate commands. The outer most loop is an altitude, heading, sideslip, and velocity command control system. Gains for the rate controllers and the outer-loop controllers can be adjusted by changing parameters in the parameter input file. New vehicle dynamics can be introduced by changing the physical and aerodynamic parameters. When new parameters are introduced, the control system uses control allocation to reconfigure for different numbers of control effectors and the dynamic inversion controller compensates for changes in response to control inputs.

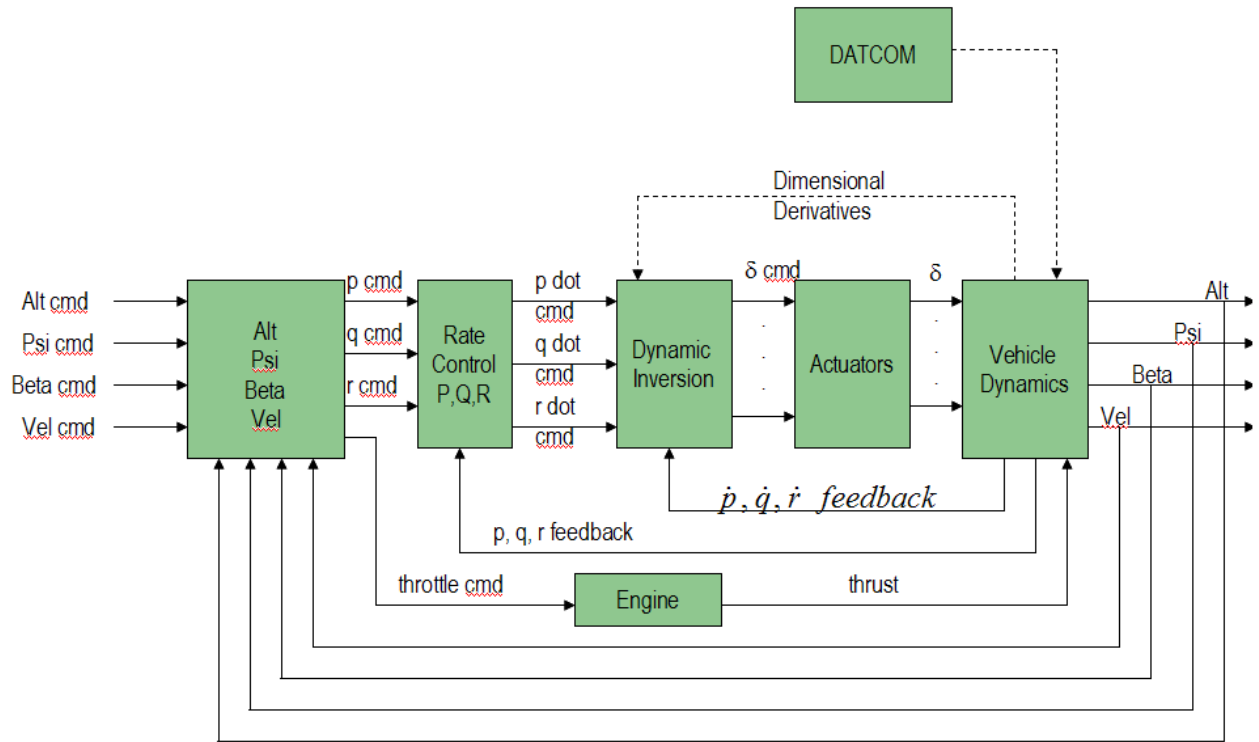


Figure 5.1: VCVS Schematic.

5.4 Sensor Footprint

The sensor footprint is implemented in a class in C++, i.e. `CSensorFootprint`. This class contains functions that can calculate rectangular or circular sensor footprints. To check if targets are in the circular footprint the function compares the difference between each of the target positions and the calculated center of the footprint. If this distance is less than the sensor radius then the target is in the footprint. The rectangular footprint function transforms the coordinates of the targets into a coordinate system aligned with the rectangular footprint. After transformation the coordinates of each target are compared to the limits of the sensor and any targets inside the limits are reported.

Chapter 6

Modifications To The Simulation

6.1 Modifying Simulation Blocks

To modify the vehicle blocks in the simulation do the following:

1. Make changes in the block `UAV1`
2. Open the library: `MultiUAV/MultiUAVDLLs/cooperative.mdl`
3. Unlock the library, i.e. *Edit* \rightarrow *Unlock Library*
4. From the library, delete the block `UAV1`.
5. From `MultiUAV2` copy the block `UAV1` and paste it into the library.
6. Close and save the library.
7. Update `MultiUAV2`

To modify the targets blocks follow the above directions, but modify and copy the block `Target1`. To add new connections between the vehicles use the following procedures:

1. Add any new outputs to the block `UAV1`.
2. Use the above steps to update the blocks.
3. Make the required connections in the block `UAV1`.
4. Use the above steps to update the blocks.

6.2 Compiling the Simulation

Instructions to compile the simulation code follow. These guides are divided into two platforms:

1. Microsoft Visual C++ (MSVC++) for Windows, and
2. any Unix like operating system using `make`, and having a C and C++ compiler.

6.2.1 Microsoft Visual C++ for Windows

For MSVC++ version 6 or higher, the process is straight-forward:

1. From `WindowsExplorer`, open the file `MultiUAVDLLs.dsw` in the `src` directory.
2. Following the *Project* menu, select *Set Active Project* → *Master*; this may also be performed through the *Build* toolbar.
3. Set the output version of the active project to *Win32 Release*, also via the *Build* toolbar.
4. Select *Build* → *Build* or type **F7** to update the output object code in the event of changes, or choose *Build* → *Rebuild All* to rebuild all of the libraries from scratch.

In many cases, the actions outlined above can be accomplished by use of the appropriate short-cut keys or toolbar buttons.

6.2.2 Unix-like

The build system for Unix-like platforms is a bottom-up composition of subsystem *makefiles* that is controlled by a top-level `Makefile`. Environmental settings and compiler/linker options are managed by the `make.env` and `make.opts` include files, respectively. In general, we expect to be using `GCC` as the compiler suite, but this can be changed in the environmental configuration options. In general, the steps to build the system are as follows:

1. In `make.env`:
 - (a) set the value of `TOP` to the full-path to the top-level `MultiUAV` directory.
 - (b) configure the C++ and C compilers in `CXX` and `CC`, respectively.
 - (c) set the value of `TWM_ROOT` to the full-path to the top-level of your `MATLAB` installation.
 - (d) specify the library platform target in `LIB_DIR_REL`, e.g. `LIB_DIR_REL = /lib/linux`.
 - (e) generally, these are the only user modifications necessary here.
2. In `make.opts`:
 - (a) set the value of `MAT_DEFS` to reflect the `MATLAB` version you are using, as compared to the required `V5` interface.
 - (b) configure the compiler options as desired for debug vs. optimized, architecture, shared library options, floating-point unit control, and additional link libraries, compiler defines or include directories.
3. The first time the system is to build, dependency files must be generated. These subsystem local `.depend` files are created by typing:

```
$ cd src
$ make dep
```

4. After which time, the entire system, including testing programs, can be built by entering:

```
$ make all
```

or simply

```
$ make
```

5. Any further changes to the code will only rebuild and relink material that directly depended on the altered code.
6. Individual subsystem can be built from the top down as needed, e.g. to only build the `CapTranShip` subsystem:

```
$ cd CapTranShip
$ make
```

6.3 Debugging the Simulation

There are three different debug facilities that can be used to debug the MultiUAV2 simulation, one each for MATLAB, SIMULINK and compiled MEX/S-functions. The compiled MEX/S-functions¹ require platform specific debuggers usually associated the compiler used, e.g. Microsoft Visual C++ (MSVC++) Debugger for Windows or GNU `gdb` for code compiled with GNU `gcc`.

MATLAB Debugger To debug m-file, one can use the built-in debugger in MATLAB. To use this debugger, open the m-file using the MATLAB menu, i.e. from the MATLAB menu select *File* → *Open* and then select the desired m-file. This will open the m-file in MATLAB's editor. Break points can be set in the file to stop the simulation when they are encountered. During the simulation, one can press the pause button on the SIMULINK interface, at a desired time, and then set break points in the m-files. NOTE: the command `clear functions` is given during start-up initialization, in the function `SimulationFunctions`, every time the SIMULINK simulation is started. This clears persistent variables in the simulation and any set breakpoints. Therefore, to stop at a breakpoint during the simulation, one must either set a breakpoint in `SimulationFunctions` after the `clear functions` command or use the SIMULINK debugger to stop SIMULINK so a breakpoint can be set.

SIMULINK Debugger To debug SIMULINK model connections the SIMULINK debugger must be used. To do this, start the SIMULINK debugger on the model MultiUAV2 with the following command: `sldebug 'MultiUAV'`. The SIMULINK Debugger commands can be found in the Using SIMULINK Manual, Chapter 11 SIMULINK *Debugger*.

MSVC++ Debugger To debug compiled S-functions use the debugger in Microsoft Visual C++ (MSVC++). To do this, follow these steps:

1. In MSVC++, open the workspace containing the project for the desired DLL.
2. Set the *DebugDLL* version of the desired DLL's project as the active project.
3. Open the *Project Settings* dialog window for the desired DLL and make the following settings:
 - Executable for Debug session: `C:\MATLAB\bin\matlab.exe`

¹For additional information about platform specific debugging of MEX/S-functions, see the MATHWORKS technical note 1819: *How Do I Debug C MEX S-functions?* at <http://tinyurl.com/2g6k9> (google cache link).

- Working Directory: `C:\UAV\MultiUAV` (the path to the `MultiUAV` directory)
4. Start the debugger. This will start MATLAB in the correct directory, so type `run` and then start the simulation as usual. Break points can be set in the DLL source files to stop the simulation for debugging.

GNU `gdb` Debugger Debugging compiled S-functions with GNU `gdb` from within MATLAB is slightly more complicated than doing so with MSVC++. The following steps outline the general procedure:

1. Rebuild the required MEX-file(s) and libraries with the `-g` option; `-g3` provides more robust debug information in the object code. This can be done by setting:

```
COMPILE_FLAGS = ${DEBUG_COMPILE_FLAGS}
```

in the file `src/make.opts` line 67.

2. start MATLAB with the `gdb` debugger in the `m-file` directory, rather than the usual `MultiUAV` directory

```
$ cd m-file
$ matlab -Dgdb
```

If you are using a debugger other than `gdb`, substitute that name after the `-D` option.

3. Once the debugger has loaded, continue loading MATLAB by typing

```
(gdb) run
Starting program: /path/to/matlab
.
.
(no debugging symbols found)...[New Thread 1024 (LWP 21412)]
```

If you do not require use of the Java front-end, and do not wish to wait for the splash screen, continue the initial load of MATLAB by instead typing

```
(gdb) run -nojvm -nosplash
```

4. After MATLAB starts, enable MEX debugging by typing the following at the command prompt:

```
>> InitializeGlobals
>> dbmex on
```

This will initialize the simulation and enable MEX debugging.

5. Run the simulation as normal, e.g. select *Run Simulation* from the GUI.
6. Periodically, the process will enter the debugger as shared library entry points are found, e.g.:

```
Program received signal SIGUSR1, User defined signal 1.
0x40ccd621 in kill () from /lib/libc.so.6
(gdb) c
Continuing.
MEX FILE: ../src/lib/linux/TacticalVehicle.mexglx entry point located
at address 0x432aa9c2
```

Load the MEX-file symbol table by issuing the following command:

```
share ../src/lib/linux/TacticalVehicle.mexglx
```

Add breakpoints at the debugger prompt and issue a "continue" to resume execution of MATLAB.

7. To place a break point in `CTacticalVehicle::waypointGetGuidance()` member function, which occurs in `src/TacticalVehicleDLL/TacticalVehicle.cpp` at line 35, enter:

```
(gdb) b TacticalVehicle.cpp:86
Breakpoint 1 at 0x4328aa5c: file TacticalVehicle.cpp, line 35.
```

If you wish to place a break point by using a function prototype, enter:

```
(gdb) b 'CTacticalVehicle::<TAB>
```

where `<TAB>` indicates that you type the TAB key to see a completion list of currently loaded symbols that begin with the `CTacticalVehicle::` namespace. The completed break point is set by typing a few more characters to disambiguate the function name and TAB-completing again to obtain:

```
(gdb) b 'CTacticalVehicle::waypointGetGuidance()'
Breakpoint 2 at 0x4329c03d: file TacticalVehicle.h, line 86.
```

8. At each remaining shared library entry point is discovered, continue the debugger

```
(gdb) c
```

9. Each time the break point is encountered, you will see:

```
Breakpoint 3, 0x4329c03d in CTacticalVehicle::waypointGetGuidance()
  (this=0x82907c8) at TacticalVehicle.h:86
86   CWaypointGuidance& waypointGetGuidance(){...};
Current language:  auto; currently c++
(gdb)
```

where you may enter debugging commands as permitted by `gdb`.

6.4 Memory Types and Usage

6.4.1 Output of Blocks

The outputs of blocks can act as memory. The value of the block outputs is held until the block is updated. If the block is disabled the output can be set to hold its last updated value.

6.4.2 Data Store Blocks

These blocks can be used to store data inside of a block which is only visible within that block and inside subsystems of that block. This is a good way to save data in an object-oriented fashion.

6.4.3 Global Memory

The use of global memory should be a *last choice* since it makes the simulation less modular and thus less flexible. For this simulation, global memory has been used for structured storage, and globally constant variables and structures. Note, the term *constant* is used to imply that the value of the variable is not intended to change during the simulation. There is no mechanism to enforce this. The following variables/structures are implemented in global memory:

6.5 Directory Structure

The supporting files for the MultiUAV2 simulation are located in various directories under the MultiUAV directory, see Figure 2.1.

6.6 Procedures for Common Modifications

6.6.1 Changing Number of Targets

1. Change the global variable `MaxNumberTargets` to the desired value. Note: `MaxNumberTargets` is initialized in the function `InitializeGlobals`.
2. Reinitialize the simulation, i.e. run the script `XtremeReinitialize`.
3. Open the MultiUAV2 SIMULINK diagram, i.e. `s-model/MultiUAV.mdl`, and/or update the diagram.
4. Add a new, or copy of an existing, target block to the `Targets` block, i.e. `MultiUAV.Targets`.
5. Add/change the code in `InitializeGlobals` required to initialize the new target(s).

6.6.2 Changing Number of Vehicles

1. Change the global variable `MaxNumberVehicles` to the desired value. Note: `MaxNumberVehicles` is initialized in the function `InitializeGlobals`. Also change the number of active vehicle in the variable `g.ActiveVehicles`.
2. Reinitialize the simulation, i.e. run the script `XtremeReinitialize`.
3. Open the MultiUAV2 SIMULINK diagram, i.e. `s-model/MultiUAV.mdl`, and/or update the diagram.
4. Add a new, or copy of an existing, vehicle block to the `Vehicles` block, i.e. `MultiUAV.Vehicles`.
5. Add/change the code in `InitializeGlobals` required to initialize the new vehicle(s).

6.6.3 Adding New Types of Vehicles/Targets

Follow the procedures for changing number of vehicles/targets, but add a new/modified block. It is probably best to make a copy of the existing blocks and then modify the copy. Make sure to implement any new messages required by the new vehicle/target.

6.6.4 Changing Targets Dynamics

Target dynamics are implemented in the function `TargetPostionS`. By default the targets are stationary, but this can be changed by adding dynamics to the `TargetPostionS` function.

6.6.5 Adding a New Assignment Algorithm

Most of the assignment algorithms implemented in the `MultiUAV2simulation` are contained in the `Calculate Assignment` block of the `CooperationManager`, i.e. `MultiUAV.Vehicles.UAV1.EmbeddedFlightSoftware.CooperationManager.Calculate Assignment`. This is the best place to add a new assignment algorithm. To add the new algorithm:

1. Open the file `CreateStructure.m` and add a new assignment type to the `Assignment-TypeDefinitions` structure. item Reinitialize the simulation, i.e. run the script `XtremeRe-initialize`.
2. Add a new enabled subsystem containing the new assignment algorithm to the `Calculate Assignment` block.
3. Make the connections necessary to enable the new assignment block when the new assignment type is selected in the `AssignmentAlgorithm` global variable.

6.6.6 Changing Sensor Simulation

The sensor simulation consists of a sensor footprint and a simple automatic target recognition (ATR) simulation. To change the sensor footprint see the next section. The ATR simulation is contained in the block `ATRSingle`, `MultiUAV.Vehicles.UAV1.EmbeddedFlightSoftware.Sensor-Manager.ATRSingle`, and is implemented in the function `ATRFunctionsSingleS`. The `ATRSingle` block uses the following information: which targets are in the sensor, the relative heading of the targets and the sensing vehicle, and the truth state of the target. This configuration can be used by other type of sensor simulations.

6.6.7 Changing Sensor Footprint

The sensor footprint is implemented in C++ as part of the `TacticalVehicleDLL` s-function. It is implemented in the files `SensorFootprint.cpp` and `SensorFootprint.h`. These files can be found in the directory `MultiUAV2/src/TacticalVehicleDLL`. To change the sensor footprint:

1. Modify an existing, or add a new, sensor case in the function `CSensorFootprint::Sensor`.
2. Add a new sensor type the enumerated list, i.e. `enSensorType` in the file `SensorFootprint.h`.
3. Change the default sensor in the `Sensor` class constructor to the new type.
4. Recompile the `TacticalDLL` s-functions.

6.6.8 Changing Vehicle Dynamics

Vehicle dynamics are governed by two files, `DATCOM.dat` and `Parameters.dat`. To change vehicle dynamics create a new `DATCOM.dat` file with the aerodynamic forces and moments and a new `Parameters.dat` with physical and control gain parameters. Alternatively, the dynamics

can be changed by changing the Vehicle & Tactical Maneuvering Dynamics s-function block, i.e. `MultiUAV.Vehicles.UAV1.Aircraftdynamics.Vehicle & Tactical Maneuvering Dynamics`.

6.6.9 Changing Initial Search Pattern

The initial search pattern is generated in the function `CalculateWaypoints`. There is a switch statement in `CalculateWaypoints` that is used to select the initial search pattern. To add a new search pattern, add a new case to this switch function.

6.6.10 Changing Simulation Sample Time

`MultiUAV2` is setup to be a fixed time step simulation with no continuous states. The fixed time step is set using the global variable, `GlobalSampleTime`. `GlobalSampleTime` is nominally set to 0.1 seconds. Changing the value in `GlobalSampleTime` and reinitializing the simulation will change the sample time. Note: changing the sample time can cause unexpected results, i.e. targets not being discovered, vehicles flying in circles, etc.

6.6.11 Adding Communication Messages

1. Open the file `CreateStructure.m`
2. Decide on the message structure to use, i.e. either `g_CommunicationsMemory` for simulated communication messages or `g_TruthMemory` for simulation truth information.
3. Add new message structure as a case in the switch structure, i.e.:

```
case 'MSG_PositionID'           % new message structure
    NewStructure = struct( ...
        'Title','PositionID',...
        'ID',0, ...
        'Enabled',1, ...
        'NumberSenders',MaxNumberVehicles, ...
        'Data',{[]}, ...
        'IndexStorageID',[1], ...
        'IndexStorageTimeStamp',[2], ...
        'VehicleIDIncluded',[1], ...
        'IndexNorth',[2], ...
        'IndexEast',[3], ...
        'IndexHeading',[4], ...
        'NumberEntries',(4), ...
        'SizeToPreAllocate',(AllocationsPer100Sec*5*g_ActiveVehicles), ...
        'TotalNumberMessagesAllocated',0, ...
        'LastMessageIndex',0, ...
        'DefaultMessage',[], ...
        'MessageDelay',0 ...
    );
```

4. Add a call to `CreateStructure()` with the new case label to the `NewStructure.Messages` cell array, for the selected message structure, i.e.

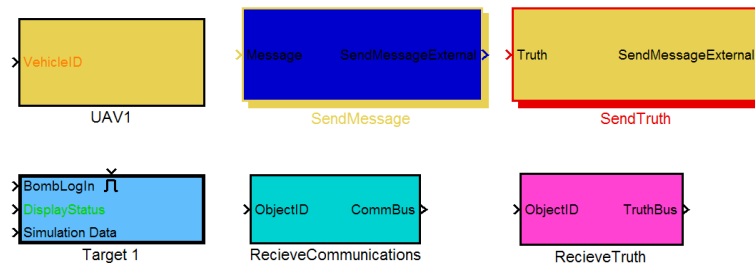


Figure 6.1: Cooperation Library.

```
NewStructure.Messages = { ...
    CreateStructure('MSG_ETACostToSearch');
    CreateStructure('MSG_PositionID');
    CreateStructure('MSG_PositionID')
};
```

Note: The last entry in this cell array does not have a semicolon.

5. Save the file `CreateStructure.m`
6. Reinitialize the simulation, i.e. run the script `XtremeReinitialize`.
7. Open and unlock the cooperation library, see Fig 6.1, i.e. `s-model/Cooperative.mdl`
8. Edit the mask of the send block corresponding to the target message structure, i.e. `SendMessage` for `g_CommunicationsMemory` or `SendTruth` for `g_TruthMemory`.
9. Select the *Initialization* tab. Select *select message type: ...* in the prompt window. Add the new message's *Title* string to the *Popup strings:*, separated by a |, i.e. `ETACostToSearch|PositionID`
10. Open the `MultiUAV2` SIMULINK diagram, i.e. `s-model/MultiUAV.mdl`, and/or update the diagram.
11. Disable the library link to one of the receive blocks, for the target structure type, i.e. `MultiUAV.Vehicles.UAV1.RecieveMessages.RecieveCommunications` for `g_CommunicationsMemory`, or `MultiUAV.Vehicles.UAV1.RecieveTruth.RecieveTruth` for `g_TruthMemory`.
12. Edit the receive block to add the new connections and lables.
13. Restore the library link and choose *Update Library*.
14. Add the new blocks required to send the message. Note: the send blocks can be configured for a static or growing message que and a drop down menu is used to select the message, see Figures 4.7 and 4.6.
15. Add/Change blocks to process the new message.

Appendix A

M-Function Reference

ATRFunctions.m - calculates single and multiple ATR values and BDA values.

AVDSData2Workspace.m - This function saves AVDS Playback data from SIMULINK to the Global Workspace.

CalculateAttackHeading.m - calculate the best heading(s) to attack a target.

CalculateBDAHeading.m - calculate the best heading(s) to BDA a target.

CalculateBenefit.m - called by CapTransShip.m to calculate benefit of assignment.

CalculateDistanceToGo.m - calculates the distance to the assigned target stand-off point calculates the distance from the vehicle's current position to the assigned target stand-off point.

CalculateWaypoints.m - calculates and saves waypoints that represent initial search patterns for the vehicles.

CapTransShipIO.m - used to setup the inputs to the CapTransShip s-function.

CreateExplosion.m - this functions calculates the vectors necessary to display an explosion in AVDS.

CreateStructure.m - create a new copy of a structure of the given type. This function is used to aggregate all of the structure creation to make it easier to track memory usage.

CreateVehicleGraphic.m

FindRequiredTask.m - this function returns a task type based on the given target state.

GUIMultiUAV.m - This is the callback function for the graphical user interface.

InitializeGlobals.m - this script sets up the MultiUAV2 global simulation variables and structures.

InitializeTargets.m - sets the position, orientation and type of the targets.

InitializeTargetTypes.m - sets the target type data in the global target type array.

MinimumDistance.m - calculates the optimal trajectory to cause a vehicle's sensor to pass over a target in a given direction.

MinimumDistanceCircle.m - calculates the trajectory for a vehicle between two points, given direction and stand-off constraints.

ModifySearchWaypoints.m - modifies return to search waypoints to change search scenarios.

PlotOutput.m - animates the vehicle trajectories and target data from the MultiUAV2 simulation.

PlotProbabilityCorrectTarget.m - plots the probability correct target for rectangular targets.

ProbabilityCorrectTarget.m - calculates probability of correct target report given viewing aspect angle. This is implemented for a rectangular target.

ReplanRoutes.m - calculates and saves the cooperation metrics and trajectories to all of the known valid targets.

RouteSelection.m - selects waypoints to use for the assigned action.

run.m - this script sets up the MultiUAV2 global simulation parameters/memory and opens the GUI figure which calls other initialization functions.

RunSimulinkDebugger.m - this function starts the SIMULINK debugger, used to remember the command.

SaveAVDSData.m - saves the AVDS playback from the global workspace to a file and creates an AVDS playback configuration file.

SearchBenefit.m - calculates value of searching relative to other tasks.

SimulationControl.m - this function is used to restart the simulation during monte carlo runs.

SimulationFunctions.m - used to initialize global simulation structures.

Summary.m - This function writes the final results of each run to a file.

TargetBombed.m - calculates the status of the target, alive or dead.

TargetBombedLog.m - tracks bomb drops.

TargetPositon.m - returns the true position of a target based on its ID number.

TargetStatus.m - monitors the status of the targets. Replan is necessary if any new targets are discovered.

TargetStatusCheck.m - checks the status of the targets for output.

TargetStatusState.m - calculates the state of a target based on past state and other data.

TaskBenefit.m - calculate the benefit of the specified vehicle performing a specified task on the specified target.

TestMinimumDistance.m - this is a simple function to debug the functions **MinimumDistance** & **CalculateDistance**.

TestTargetAngles.m - this is a simple function to debug the target angle/template functions

TestVehicleGraphics.m - this is a simple function used to debug the **CreateVehicleGraphic** function

TestWaypoints.m - this is a simple function to debug the functions **MinimumDistance** & **CalculateDistance**.

WaypointsAddMinSeparation.m - adds extra waypoints along the circular segments of the trajectory. In order to cause the vehicle to better track the commanded trajectory, extra waypoints are added to the circular portions of the trajectory.

WeaponsRelease.m - calculate truth results for weapons release.

WritePlaybackInit.m - creates and adds to an AVDS Playback configuration file.

Appendix B

Global Variables Reference

| | |
|---|---|
| <code>g_ActiveTargets</code> | (constant 1x1) The number of active Targets. Allows the user to use less than the <code>g_MaxNumberTargets</code> . |
| <code>g_ActiveVehicles</code> | (constant 1x1) The number of active Vehicles. Allows the user to use less than the <code>g_MaxNumberVehicles</code> . |
| <code>g_ASSERT_STATUS</code> | Controls the operation of assertions. Used for debugging. |
| <code>g_AssignmentAlgorithm</code> | (constant 1x1) The active assignment algorithm, see <code>TypeAssignment</code> for assignment algorithm types. |
| <code>g_AssignmentDelayEstimate</code> | (constant 1x1) Used by distributed algorithms. Estimate of the time it will take to compute the assignment. |
| <code>g_AssignmentTimeDelay</code> | (constant 1x1) The maximum time difference allowed between time stamps on assignment data from the vehicles. |
| <code>g_AssignToSearchMethod</code> | (constant 1x1) Used by distributed algorithms. |
| <code>g_ATRThreshold</code> | (constant 1x1) The threshold to declare a target classified. |
| <code>g_AVDSTargetCells</code> | (cell array <code>g_MaxNumberTargets</code> x1) Used to store target data for AVDS playback. |
| <code>g_AVDSVehicleCells</code> | (cell array 8x1) Used to store vehicle data for AVDS playback. |
| <code>g_BDAFalseReportPercentage</code> | (constant 1x1) The percentage of time BDA sensor will provide a false report [0.0, 1.0]. |
| <code>g_CommandTurnRadius</code> | (constant 1x1) The desired turn radius, in feet. |
| <code>g_BiddingIncrement</code> | (constant 1x1) Used by distributed algorithms. |
| <code>g_CommDelayDiscHoldOrder</code> | (constant 1x1) Discrete hold order to delay calculation of the cooperation assignment algorithm. |
| <code>g_CommDelayMajorStepsOther</code> | (constant 1x1) Fixed communication delay, measured in major model updates. |
| <code>g_CommDelayMajorStepsSelf</code> | (constant 1x1) Fixed local communication processing delay, measured in major model updates. |
| <code>g_CooperativeATR</code> | (constant 1x1) Turns off (0) or On (1) the vehicles' ability to use other vehicles single ATR values in the combined ATR calculation. |
| <code>g_CoordinationDelayDen</code> | (constant 1x?) Discrete n -order hold, i.e. coefficients of the denominator monomial. Note this is specified by <code>g_CommDelayDisc-</code> |

| | |
|---|--|
| | HoldOrder. |
| <code>g_Debug</code> | (constant 1x1) A flag used to turn on/off debug printouts. |
| <code>g_DefaultMach</code> | (constant 1x1) If there is no Mach number chosen for waypoints this value is used. |
| <code>g_DefaultWaypointAltitude</code> | (constant 1x1) If there is no Altitude chosen for waypoints this value is used. |
| <code>g_EnableTarget</code> | (constant 10x1) In this array, the elements correspond to the targets. If the element is set equal to 0, the target is disabled. To enable the target the element is set equal to a Target ID number. |
| <code>g_EnableTargetDefault</code> | (constant <code>g_MaxNumberTargets</code> x?) IDs of the targets to enable by default. |
| <code>g_EnableVehicle</code> | (constant 8x1) In this array, the elements correspond to the vehicles. If the element is set equal to 0, the vehicle is disabled. To enable the threat the element is set equal to a <i>Vehicle ID</i> number. |
| <code>g_EnableVehicleDefault</code> | (constant 8x1) IDs of the vehicles to enable by default. |
| <code>g_isMonteCarloRun</code> | (constant 1x1) Flag used to setup simulation for a Monte-Carlo simulation. |
| <code>g_LengthenPaths</code> | (constant 1x1) Flag used to enable path lengthening in the trajectory planning algorithm. |
| <code>g_MaxNumberDesiredHeadings</code> | (constant 1x1) Maximum number of desired headings for target classification. |
| <code>g_MaxNumberTargets</code> | (constant 1x1) Maximum number of targets allowed in the simulation. |
| <code>g_MaxNumberVehicles</code> | (constant 1x1) Maximum number of vehicles allowed in the simulation. |
| <code>g_MaxReassignmentDeltaTime</code> | (constant 1x1) Maximum time between reassignments. |
| <code>g_MetersToFeet</code> | (constant 1x1) Used to convert from meters to feet. |
| <code>g_NumberTargetOutputs</code> | (constant 1x1) Number of outputs from target blocks. |
| <code>g_OneTimeInitialization</code> | (constant 1x1) Flag used to insure that certain initialization function are only executed once. |
| <code>g_OptionAssignmentWeight</code> | (constant 1x1) Controls how assignment weights are calculated (<code>CapTransShipIO.m</code>). |
| <code>g_OptionBackToSearch</code> | (constant 1x1) Controls how vehicles return to search (<code>RouteSelection.m</code>) |
| <code>g_OptionModifiedWaypoints</code> | (constant 1x1) Set to a non-zero value to force the use of search waypoints that are modified in the function <code>ModifySearchWaypoints()</code> . |
| <code>g_OptionSaveDataAVDS</code> | (constant 1x1) Controls saving of AVDS data. Turning this off will increase simulation speed. |
| <code>g_OptionSaveDataPlot</code> | (constant 1x1) Controls saving of plot data. Turning this off will increase simulation speed. |

- `g_PauseAfterEachTimeStep` (constant 1x1) Flag the causes SIMULINK to go into *pause* mode at the end of each major time step.
- `g_PlotAxesLimits` (constant 1x4) These are the limits for the axes in the animated plot.
- `g_ProbabilityID` (constant 5x5) A matrix of probabilities that an encounter with a target will result in an estimate of a given target type, i.e. Confusion matrix.
- `g_ProbabilityOfKill` (constant 1x1) Probability that a bomb drop will kill a target if it is within the bomb's kill radius of the target.
- `g_SampleTime` (constant 1x1) The sample time used for all of the blocks by default.
- `g_SaveAlgorithmTime` (variable 1x1) Storage for time it takes to execute the multiple task tour assignment algorithms.
- `g_SaveAlgorithmTimeFlag` (constant 1x1) Flag to control saving the time it takes to execute the multiple task tour assignment algorithms.
- `g_Scenario` (constant 1x1) Counter for Monte-Carlo scenario number.
- `g_SearchSpace` (constant 1x4) Rectangular area searched by the vehicles.
- `g_Seed` (constant 1x1) Seed for the random number generator. With no changes to the simulation, using the same seed in different simulation runs will produce the same random configuration.
- `g_SensorLeadingEdge_ft` (constant 1x1) Position of the leading edge of the sensor footprint, in feet, with respect to the center of gravity of the vehicles. Note: This value is only used as a convenience for calculations the actual sensor configuration is set in the `TacticalVehicleDLL`, see §5.4.
- `g_SensorRollLimitDeg` (constant 1x1) The amount a vehicle can roll before the sensor is disabled (degrees).
- `g_SensorTrailingEdge_ft` (constant 1x1) Position of the trailing edge of the sensor footprint, in feet, with respect to the center of gravity of the vehicles. Note: This value is only used as a convenience for calculations the actual sensor configuration is set in the `TacticalVehicleDLL`, see §5.4.
- `g_SensorWidth_ft` (constant 1x1) Width of the sensor footprint, in feet. Note: This value is only used as a convenience for calculations the actual sensor configuration is set in the `TacticalVehicleDLL`, see §5.4.
- `g_SensorWidth_m` (constant 1x1) Width of the sensor footprint, in meters. Note: This value is only used as a convenience for calculations the actual sensor configuration is set in the `TacticalVehicleDLL`, see §5.4.
- `g_SimulationRunNumber` (constant 1x1) Counter to keep track of simulation runs during Monte-Carlo simulations.
- `g_SimulationTime` (constant 1x1) Current simulated time, in seconds, of the simulation run. SIMULINK updates this time during calls to the function, `InitFunctionsS`.
- `g_StopTime` (constant 1x1) The time to stop the simulation.

`g_SummaryFileName` (constant char array)
`g_TargetPositions` (`g_MaxNumberTarget` x `g_TargetPositions.Numberentries`) used to predefine positions of the targets. Used during initialization.
`g_TargetSpace` (constant 1x4) Rectangular region limits for random target placement.
`g_VerificationOn` (constant 1x1) Flag to turn On/Off verification in the function, `TaskBenefit`.
`g_WaypointCells` (cell 8x1) These cells are used to store the current waypoints for each vehicle. The vehicle s-function reads the waypoints from these cells.
`g_WaypointFlags` (constant 8x1) This is an array of flags used by each vehicle to signal that new waypoints have been entered in the vehicle's element of the `g_WaypointCells`.
`g_WaypointStartingIndex` (constant 8x1) This is the waypoint index used when waypoints are reinitialized in `TacticalVehicleDLL`.

Appendix C

Global Structures Reference

C.1 Vehicle Memory (g_VehicleMemory)

(array of structures) The *main* memory for the vehicle blocks. Each structure in this array is used as memory for a vehicle. The structures contain structures for each of the managers. This gives each manager a structure for data storage.

`g_VehicleMemory(:)`.

```
    VehicleType: 2
    Dynamics: [1x1 struct], see §§C.1.1
    WeaponsManager: [1x1 struct], see §§C.1.2
    TargetManager: [1x1 struct], see §§C.1.3
    CooperationManager: [1x1 struct], see §§C.1.4
    RouteManager: [1x1 struct], see §§C.1.5
    SensorManager: [1x1 struct], see §§C.1.6
    TacticalManeuveringManager: []
    MonteCarloMetrics: [1x1 struct], see §§C.3
```

C.1.1 Dynamics Structure

`g_VehicleMemory(:).Dynamics.`

```
    VTrueFPSInit: 370
    PsiDegInit: 0
    PositionXFeetInit: -4.593175853000000e+003
    PositionYFeetInit: -9.8425196850000001e+002
    PositionZFeetInit: 675
    NumberBombsInit: 1
    FuelLB: 15000
```

C.1.2 Weapons Manager Structure

`g_VehicleMemory(:).WeaponsManager.`

```
    NumberBombsDropped: 1
```

C.1.3 Target Manager Structure

```
g_VehicleMemory().TargetManager.
    LastCompletedTask: 0
        TotalAttacks: [10x1 double]
        SensedTargetType: [10x1 double]
    LastReportedState: [10x1 double]
```

C.1.4 Cooperation Manager Structure

```
g_VehicleMemory().CooperationManager.
    AssignmentTimeDelay: 4.000000000000000e-001
        WaypointMemory: {8x1 cell}
        SavedHeading: [8x10x6 double]
        TaskList: [10x4 double]
    TargetSchedule: []
        ReplanRound: [0 0]
    LastRoundComplete: [0 0]
    AuctionInformation: [1x1 struct]
        CurrentBenefits: [1x1 struct]
        AuctioneerDuty: []
        MessageNumber: 0
    PendingWaypoints: [42x12 double]
```

C.1.5 Route Manager Structure

```
g_VehicleMemory().RouteManager.
    TargetIDSaved: [10x1 double]
        PsiSaved: [10x1 double]
    CommandTurnRadius: 2000
    AssignmentTimeDelay: 5.000000000000000e-001
        SaveWaypoints: []
    UsingOriginalSearchWaypoints: 0
        AlternateWaypoints: [32x12 double]
    AlternateWaypointIndex: 2
    OffsetToAlternateIndex: 11
        LastSearchX: 1.504390255589156e+004
        LastSearchY: -9.842519719314307e+002
        LastSearchZ: 675
        LastSearchPsi: 1.570796325902963e+000
    AssignedTarget: -1
    AssignedTask: -1
```

C.1.6 Sensor Manager Structure

```
g_VehicleMemory().SensorManager.
    NumberSightings: [10x8 double]
    ATRSingleTime: [10x8x4 double]
```

```

        ATRSingleMetric: [10x8x4 double]
    ATRSingleViewingAngle: [10x8x4 double]
        ATRSingleEstPose: [10x8x4 double]
        ATREstTargetType: [10x8x4 double]
            BDASave: [10x10 double]

```

C.2 Vehicle Input Files Structures

This structure contains two substructures and is used to configure parameters for the vehicle dynamics simulation functions.

C.2.1 g_VehicleInputFiles

```

g_VehicleInputFiles =
    datcom: [1x1 struct]
    params: [1x1 struct]

```

C.2.2 DATCOM Input Parameters

```

g_VehicleInputFiles.datcom.
    name: '..\InputFiles\DATCOM.dat'
    version: 1
    isSubtractBaseTables: 1

```

C.2.3 Parameter Inputs

```

g_VehicleInputFiles.params.
    name: '..\InputFiles\Parameters.dat'
    version: 1.4000000000000000e+000

```

C.3 Monte-Carlo Metrics (g_MonteCarloMetrics)

This structure is used to save data during Monte-Carlo simulations.

```

g_MonteCarloMetrics =
    TotalSearchTimeSeconds: 0
    AliveTimeSeconds: 0
    TargetStateTimes: []
    Target1PostionHeading: [10x1 struct]
    NumberAuctionCalls: 0
    TotalNumberAuctionBids: []
    RecalculateTrajectory: 0
    SaveMultipleTaskDataFlag: 0
    LastMultipleTaskSaveTime: 0
    MultipleTaskSaveCount: 0
    MultipleTaskSaveFile: 'SaveSingle'
    MultipleTaskSaveFileVersion: 1
    DirectoryName: 'MonteCarloData'

```

C.4 Entity Types (g_EntityTypes)

A structure that enumerates all available entity types in the simulation.

```
g_EntityTypes =
    Aircraft: 1
    Munition: 2
    Target: 3
    NumberEntities: 3
```

C.5 Color Structures

C.5.1 g_Colors

This structure contains color definitions used in the simulation.

```
g_Colors =
    LightGray: [6.40000000e-001 6.40000000e-001 6.40000000e-001]
    LightRed: [6.40000000e-001 0 0]
    LightGreen: [0 6.40000000e-001 0]
    LightBlue: [0 0 6.40000000e-001]
    LightYellow: [6.40000000e-001 6.40000000e-001 0]
    LightMagenta: [6.40000000e-001 0 6.40000000e-001]
    LightCyan: [0 6.40000000e-001 6.40000000e-001]
    LightOrange: [8.00000000e-001 4.00000000e-001 2.00000000e-001]
    DarkGray: [4.00000000e-001 4.00000000e-001 4.00000000e-001]
    DarkRed: [4.00000000e-001 0 0]
    DarkGreen: [0 4.00000000e-001 0]
    DarkBlue: [0 0 4.00000000e-001]
    DarkYellow: [4.00000000e-001 4.00000000e-001 0]
    DarkMagenta: [4.00000000e-001 0 4.00000000e-001]
    DarkCyan: [0 4.00000000e-001 4.00000000e-001]
    DarkOrange: [4.00000000e-001 1.60000000e-001 8.00000000e-002]
    Black: [0 0 0]
    WhiteDull: [9.00000000e-001 9.00000000e-001 9.00000000e-001]
    White: [1 1 1]
    AVDSLighGray: 4.288914339000000e+009
    AVDSLighRed: 4.278190243000000e+009
    AVDSLighGreen: 4.278231808000000e+009
    AVDSLighBlue: 4.288872448000000e+009
    AVDSLighYellow: 4.278231971000000e+009
    AVDSLighMagenta: 4.288872611000000e+009
    AVDSLighCyan: 4.288914176000000e+009
    AVDSLighOrange: 4.281558732000000e+009
    AVDSDarkGray: 4.284900966000000e+009
    AVDSDarkRed: 4.278190182000000e+009
    AVDSDarkGreen: 4.278216192000000e+009
    AVDSDarkBlue: 4.284874752000000e+009
```

```

    AVDSDarkYellow: 4.278216294000000e+009
    AVDSDarkMagenta: 4.284874854000000e+009
    AVDSDarkCyan: 4.284900864000000e+009
    AVDSDarkOrange: 4.279511142000000e+009
    AVDSBlack: 4.27819008e+009
    AVDSWhiteDull: 4.293256677000000e+009
    AVDSWhite: 4.294967295000000e+009
    AVDSRed255: 255
    AVDSGreen255: 65280
    AVDSBlue255: 16711680
    AVDSTransparent255: 4.27819008e+009
    AVDSRed1: 1
    AVDSGreen1: 256
    AVDSBlue1: 65536
    AVDSTransparent1: 16777216
    ColorsAVDS: [4x1 double]

```

C.5.2 g_VehicleColors

Contains definitions for the color of the vehicles in matrix form.

```

g_VehicleColors =
    ColorVehicles: [8x3 double]
    ColorVehiclesAVDS: [8x1 double]

```

C.6 Target Structures

C.6.1 Global Target Position Definitions (g_TargetPositionDefinitions)

This structure defines the indices used in the g_TargetPositions matrix.

```

g_TargetPositionDefinitions =
    PositionX: 1
    PositionY: 2
    PositionZ: 3
    PositionPsi: 4
    PositionType: 5

```

C.6.2 Target Main Memory

The memory for simulation events that effect the all of target blocks.

```

g_TargetMainMemory =
    BombLog: [4x4 double]

```

C.6.3 Target Memory

(array of structures) The *main* memory for the individual target blocks. Each structure in this array is used as memory for a target.

```

g_TargetMemory =
    ID: 1
    PositionX: 1.855757452224400e+004
    PositionY: -2.828167393376042e+003
    PositionZ: 0
    Psi: 3.895615558219653e-001
    Type: 1
    Alive: 0
    NumberBombsChecked: 4

```

C.6.4 TargetStates

Contains information concerning the target states such as the number of states, state description strings and state index definitions.

```

g_TargetStates =
    StateStrings: {6x1 cell}
    IncAttack: 100
    IncReset: 10000
    StateUndefined: -1
    StateNotDetected: 0
    StateDetectedNotClassified: 1
    StateClassifiedNotAttacked: 2
    StateAttackedNotKilled: 3
    StateKilledNotConfirmed: 4
    StateConfirmedKill: 5
    StateUnknownTarget: 6
    NumberStates: 7
    ColorTargetStates: [8x3 double]
    ColorTargetStatesAVDS: [8x1 double]

```

C.6.5 TargetTypes

(array of structures) Each of these structures contains the information that defines the attributes of a target type. These attributes are: length, width, height, best viewing angles, a flag to differentiate targets from non-targets, and a numerical value for the target type.

```

g_TargetTypes(:) =
    Length: 20
    Width: 10
    Height: 10
    BestViewingHeadingsRad: [4x1 double]
    IsTarget: 1
    TargetValue: 10
    LethalRangeMax: []
    LethalRangeMin: []
    ProbKillMax: 2.000000000000000e-001
    ProbKillMin: 0

```


C.7 Assignment Algorithm Structures

C.7.1 g_Tasks

Contains information concerning the tasks such as the number of tasks, task description strings and task index definitions.

```
g_Tasks =
    TaskStrings: {7x1 cell}
    Undefined: -1
    ContinueSearching: 0
    Classify: 1
    Attack: 2
    Verify: 3
    TasksComplete: 4
    ClassifyAttack: 4
    NumberTasks: 5
    NotInPlay: -1
    Unassigned: 0
    Assigned: 1
    Completed: 2
```

C.7.2 g_TypeAssignment

Enumerates the different assignment algorithms implemented in the simulation.

```
g_TypeAssignment =
    CapTransShip: 1
    AuctionJacobi: 2
    ItCapTransShip: 3
    ItAuctionJacobi: 4
    RelativeBenefits: 5
    DistItCapTransShip: 6
    DistAuctItCapTransShip: 7
    NumberEntries: 7
```

C.7.3 g_AssignmentTypes

Used by the distributed algorithms.

```
g_AssignmentTypes =
    Individual: 1
    Common: 2
```

C.8 Waypoint Structures

C.8.1 g_WaypointDefinitions

Enumerates the indices of the waypoints.

```

g_WaypointDefinitions =
    PositionX: 1
    PositionY: 2
    PositionZ: 3
    MachCommand: 4
    MachCommandFlag: 5
    SegmentLength: 6
    TurnCenterX: 7
    TurnCenterY: 8
    TurnDirection: 9
    WaypointType: 10
    TargetHandle: 11
    ResetVehiclePosition: 12
    NumberEntries: 12

```

C.8.2 g_WaypointTypes

Defines the different types of waypoints available. `EndTask` and `EndTaskReplan` are qualifier flags to mark the last waypoint in the assignment. These flags are multiplied by `QualifierMultiple` before being added to the waypoint type.

```

g_WaypointTypes =
    Search: 1
    Enroute: 2
    Classify: 3
    Attack: 4
    Verify: 5
    StartPoint: 6
    EndPoint: 7
    Unknown: 8
    EndTask: 100
    EndTaskReplan: 200
    QualifierMultiple: 100

```

C.9 Communication Message Structures

These are the structures that implement message passing for communications, see Chapter 4.

C.9.1 g_CommunicationMemory

```

g_CommunicationMemory =
    InBoxes: [11x1 struct]
    Messages: {12x1 cell}
    DelayMatrix: [11x11 double]
    NumberMessages: 12
    MemoryAllocationMetric: [12x1 double]
    InBoxAllocationMetric: [11x1 double]

```

```

MsgIndicies: [1x1 struct]
Transport: [1x1 struct]

```

C.9.2 InBoxes

```

g_CommunicationMemory.InBoxes(:) =
g_TruthMemory.InBoxes(:) =
    MessageHeaders: []
    IndexTimeStamp: 1
    IndexTimeActivate: 2
    IndexMessageID: 3
    IndexMessagePointer: 4
    IndexMessageEvaluated: 5
    NumberEntries: 5
    SizeToPreAllocate: 400
    TotalNumberMessageHeadersAlloca: 800
    LastMessageHeaderIndex: 439

```

C.9.2.1 Simulation Object IDs

```

g_ObjectMessageIDs =
    VehicleIDOffset: 0
    VehicleIDFirst: 1
    VehicleIDLast: 8
    TargetIDOffset: 8
    TargetIDFirst: 9
    TargetIDLast: 9
    MiscIDOffset: 9
    DataSaveID: 10
    VehicleEnableID: 11
    NumberMessageIDs: 11
    TypeMultiplier: 10000
    VehicleType: 1
    VehicleTypeShifted: 10000
    TargetType: 2
    TargetTypeShifted: 20000
    MiscType: 3
    MiscTypeShifted: 30000
    AllVehiclesType: 4
    AllVehiclesTypeShifted: 40000
    AllTargetsType: 5
    AllTargetsTypeShifted: 50000
    NumberTypes: 5

```

C.9.3 Message Transport Type

```

g_CommunicationMemory.Transport =
g_TruthMemory.Transport =

```

```

TransportType: 0
MatlabMatrix: 0
    External: 1

```

C.9.4 Communication Message Indices

```

g_CommunicationMemory.MsgIndicies =
    ETACostToSearch: 1
        PositionID: 2
        WaypointIndex: 3
        TriggerReplan: 4
            ATRSingle: 5
            ATRTime: 6
        TargetStatus: 7
        TargetAttacked: 8
        ChangedStatus: 9
    SendPositionsFlag: 10
        TaskBenefits: 11
        AuctionData: 12

```

C.9.5 Communication Messages

The following message structures define what information is communicated between vehicles in the simulation.

C.9.5.1 Communication Message: *ETACostToSearch*

```

        Title: 'ETACostToSearch'
        ID: 1
        Enabled: 1
        NumberSenders: 8
        Data: []
        IndexStorageID: 1
        IndexStorageTimeStamp: 2
        IndexETATimeStamp: 1
        IndexETA: [2 3 4 5 6 7 8 9 10 11]
        IndexCost: [12 13 14 15 16 17 18 19 20 21]
        IndexToSearch: [22 23 24 25 26 27 28 29 30 31]
        NumberEntries: 31
        SizeToPreAllocate: 16
    TotalNumberMessagesAllocated: 0
        LastMessageIndex: 0
        DefaultMessage: []
        MessageDelay: 0

```

C.9.5.2 Communication Message: *PositionID*

```

        Title: 'PositionID'

```

```

        ID: 2
        Enabled: 1
        NumberSenders: 8
        Data: [6x80 double]
        IndexStorageID: 1
    IndexStorageTimeStamp: 2
        VehicleIDIncluded: 1
        IndexNorth: 2
        IndexEast: 3
        IndexHeading: 4
        NumberEntries: 4
        SizeToPreAllocate: 80
    TotalNumberMessagesAllocated: 80
        LastMessageIndex: 70
        DefaultMessage: []
        MessageDelay: 0

```

C.9.5.3 Communication Message: *WaypointIndex*

```

        Title: 'WaypointIndex'
        ID: 3
        Enabled: 1
        NumberSenders: 8
        Data: [3x80 double]
        IndexStorageID: 1
    IndexStorageTimeStamp: 2
        IndexWaypointIndex: 1
        NumberEntries: 1
        SizeToPreAllocate: 80
    TotalNumberMessagesAllocated: 80
        LastMessageIndex: 72
        DefaultMessage: []
        MessageDelay: 0

```

C.9.5.4 Communication Message: *TriggerReplan*

```

        Title: 'TriggerReplan'
        ID: 4
        Enabled: 1
        NumberSenders: 8
        Data: [3x16 double]
        IndexStorageID: 1
    IndexStorageTimeStamp: 2
        IndexTriggerReplan: 1
        NumberEntries: 1
        SizeToPreAllocate: 16
    TotalNumberMessagesAllocated: 16

```

```

    ReplanNoReset: 1
    ReplanReset: 2
    LastMessageIndex: 1
    DefaultMessage: []
    MessageDelay: 0

```

C.9.5.5 Communication Message: *ATRSingle*

```

    Title: 'ATRSingle'
    ID: 5
    Enabled: 1
    NumberSenders: 8
    Data: [43x32 double]
    IndexStorageID: 1
    IndexStorageTimeStamp: 2
    ATRTime: 1
    IndexSinglATR: [2 3 4 5 6 7 8 9 10 11]
    IndexSensedHeading: [12 13 14 15 16 17 18 19 20 21]
    IndexEstimatedPoseAngle: [22 23 24 25 26 27 28 29 30 31]
    IndexEstimatedType: [32 33 34 35 36 37 38 39 40 41]
    NumberEntries: 41
    SizeToPreAllocate: 32
    TotalNumberMessagesAllocated: 32
    LastMessageIndex: 12
    DefaultMessage: []
    MessageDelay: 0

```

C.9.5.6 Communication Message: *ATRTime*

```

    Title: 'ATRTime'
    ID: 6
    Enabled: 1
    NumberSenders: 8
    Data: [3x32 double]
    IndexStorageID: 1
    IndexStorageTimeStamp: 2
    IndexATRTime: 1
    NumberEntries: 1
    SizeToPreAllocate: 32
    TotalNumberMessagesAllocated: 32
    LastMessageIndex: 12
    DefaultMessage: []
    MessageDelay: 0

```

C.9.5.7 Communication Message: *TargetStatus*

```

    Title: 'TargetStatus'
    ID: 7

```

```
        Enabled: 1
        NumberSenders: 8
            Data: [12x256 double]
        IndexStorageID: 1
    IndexStorageTimeStamp: 2
        IndexTargetStatus: [1 2 3 4 5 6 7 8 9 10]
            NumberEntries: 10
            SizeToPreAllocate: 256
    TotalNumberMessagesAllocated: 256
        LastMessageIndex: 101
        DefaultMessage: []
        MessageDelay: 0
```

C.9.5.8 Communication Message: *TargetAttacked*

```
        Title: 'TargetAttacked'
        ID: 8
        Enabled: 1
        NumberSenders: 8
            Data: [3x16 double]
        IndexStorageID: 1
    IndexStorageTimeStamp: 2
        IndexTargetAttacked: 1
            NumberEntries: 1
            SizeToPreAllocate: 16
    TotalNumberMessagesAllocated: 16
        LastMessageIndex: 4
        DefaultMessage: []
        MessageDelay: 0
```

C.9.5.9 Communication Message: *ChangedStatus*

```
        Title: 'ChangedStatus'
        ID: 9
        Enabled: 1
        NumberSenders: 8
            Data: [3x256 double]
        IndexStorageID: 1
    IndexStorageTimeStamp: 2
        IndexChangedStatus: 1
            NumberEntries: 1
            SizeToPreAllocate: 256
    TotalNumberMessagesAllocated: 256
        LastMessageIndex: 97
        DefaultMessage: []
        MessageDelay: 0
```

C.9.5.10 Communication Message: *SendPositionsFlag*

```

        Title: 'SendPositionsFlag'
        ID: 10
        Enabled: 1
        NumberSenders: 8
        Data: [3x256 double]
        IndexStorageID: 1
        IndexStorageTimeStamp: 2
        IndexSendPositionsFlag: 1
        NumberEntries: 1
        SizeToPreAllocate: 256
        TotalNumberMessagesAllocated: 256
        LastMessageIndex: 70
        DefaultMessage: []
        MessageDelay: 0

```

C.9.5.11 Communication Message: *TaskBenefits*

```

        Title: 'TaskBenefits'
        ID: 11
        Enabled: 1
        NumberSenders: 8
        Data: []
        IndexStorageID: 1
        IndexStorageTimeStamp: 2
        ReplanRound: [1 2]
        TargetStates: [3 4 5 6 7 8 9 10 11 12]
        TaskBenefits: [13 14 15 16 17 18 19 20 21 22]
        TimeToComplete: [23 24 25 26 27 28 29 30 31 32]
        SearchBenefit: 33
        NumberEntries: 33
        SizeToPreAllocate: 240
        TotalNumberMessagesAllocated: 0
        LastMessageIndex: 0
        DefaultMessage: []
        MessageDelay: 0

```

C.9.5.12 Communication Message: *AuctionData*

```

        Title: 'AuctionData'
        ID: 12
        Enabled: 1
        NumberSenders: 8
        Data: []
        IndexStorageID: 1
        IndexStorageTimeStamp: 2
        TimeStamp: 1

```



```

        ReplanRound: [2 3]
        BidTarget: [4 5 6 7 8 9 10 11]
        BidPrice: [12 13 14 15 16 17 18 19]
        BidTargetETA: [20 21 22 23 24 25 26 27]
        AssignedTarget: [28 29 30 31 32 33 34 35]
        AssignedPrice: [36 37 38 39 40 41 42 43]
        AssignedTargetETA: [44 45 46 47 48 49 50 51]
        NumberEntries: 51
        SizeToPreAllocate: 480
        TotalNumberMessagesAllocated: 0
        LastMessageIndex: 0
        DefaultMessage: []
        MessageDelay: 0

```

C.10 Simulation Truth Message Structures

These are the structures that implement message passing for simulation truth, see Chapter 4.

C.10.1 g_TruthMemory

```

g_TruthMemory =
    InBoxes: [11x1 struct]
    Messages: {9x1 cell}
    DelayMatrix: [11x11 double]
    NumberMessages: 9
    MemoryAllocationMetric: [9x1 double]
    InBoxAllocationMetric: [11x1 double]
    MsgIndicies: [1x1 struct]
    Transport: [1x1 struct]

```

C.10.2 InBoxes

See §§ C.9.2.

C.10.3 Message Transport Type

See §§ C.9.3.

C.10.4 Simulation Truth Message Indices

```

g_TruthMemory.MsgIndicies =
    VehicleState: 1
    VehicleIsDead: 2
    ChangeVehicleStatus: 3
    WeaponsRelease: 4
    TargetStatus: 5
    TargetState: 6
    VehicleStateSaveData: 7

```

TrackList: 8
 ChangeAssignmentFlagSelf: 9

C.10.5 Simulation Truth Messages

The following message structures define the messages that contain simulation truth information.

C.10.5.1 Simulation Truth Message: **VehicleState**

Title: 'VehicleState'
 ID: 1
 Enabled: 1
 NumberSenders: 8
 Data: [9x8 double]
 IndexStorageID: 1
 IndexStorageTimeStamp: 2
 VehicleLinearPositions: [1 2 3]
 VehicleAngularPositions: [4 5 6]
 VehicleIsDead: 7
 NumberEntries: 7
 SizeToPreAllocate: 480
 TotalNumberMessagesAllocated: 8
 LastMessageIndex: 8
 DefaultMessage: []
 MessageDelay: 0

C.10.5.2 Simulation Truth Message: *VehicleIsDead*

Title: 'VehicleIsDead'
 ID: 2
 Enabled: 1
 NumberSenders: 8
 Data: [3x8 double]
 IndexStorageID: 1
 IndexStorageTimeStamp: 2
 VehicleIsDead: 1
 NumberEntries: 1
 SizeToPreAllocate: 480
 TotalNumberMessagesAllocated: 8
 LastMessageIndex: 5
 DefaultMessage: []
 MessageDelay: 0

C.10.5.3 Simulation Truth Message: *ChangeVehicleStatus*

Title: 'ChangeVehicleStatus'
 ID: 3
 Enabled: 1

```

        NumberSenders: 10
            Data: []
        IndexStorageID: 1
    IndexStorageTimeStamp: 2
        NewVehicleStatus: [1 2 3 4 5 6 7 8]
        NumberEntries: 8
        SizeToPreAllocate: 480
TotalNumberMessagesAllocated: 0
    LastMessageIndex: 0
        DefaultMessage: []
        MessageDelay: 0

```

C.10.5.4 Simulation Truth Message: *WeaponsRelease*

```

Title: 'WeaponsRelease'
ID: 4
Enabled: 1
NumberSenders: 8
Data: [6x8 double]
IndexStorageID: 1
IndexStorageTimeStamp: 2
WeaponID: 1
WeaponType: 2
WeaponAimPoint: [3 4]
NumberEntries: 4
SizeToPreAllocate: 480
TotalNumberMessagesAllocated: 8
LastMessageIndex: 5
DefaultMessage: []
MessageDelay: 0

```

C.10.5.5 Simulation Truth Message: *TargetStatus*

```

Title: 'TargetStatus'
ID: 5
Enabled: 1
NumberSenders: 8
Data: [12x8 double]
IndexStorageID: 1
IndexStorageTimeStamp: 2
TargetStatus: [1 2 3 4 5 6 7 8 9 10]
NumberEntries: 10
SizeToPreAllocate: 480
TotalNumberMessagesAllocated: 8
LastMessageIndex: 8
DefaultMessage: []
MessageDelay: 0

```

C.10.5.6 Simulation Truth Message: *TargetState*

```

        Title: 'TargetState'
        ID: 6
        Enabled: 1
        NumberSenders: 10
        Data: [8x10 double]
        IndexStorageID: 1
        IndexStorageTimeStamp: 2
        LinearPosition: [1 2 3]
        Type: 4
        Psi: 5
        Alive: 6
        NumberEntries: 6
        SizeToPreAllocate: 480
        TotalNumberMessagesAllocated: 10
        LastMessageIndex: 4
        DefaultMessage: [8x1 double]
        MessageDelay: 0

```

C.10.5.7 Simulation Truth Message: *VehicleStateSaveData*

```

        Title: 'VehicleStateSaveData'
        ID: 7
        Enabled: 1
        NumberSenders: 8
        Data: [14x8 double]
        IndexStorageID: 1
        IndexStorageTimeStamp: 2
        VehicleLinearPositions: [1 2 3]
        VehicleAngularPositions: [4 5 6]
        SensorOn: 7
        RabbitState: [8 9 10]
        TargetAssignment: 11
        VehicleIsDead: 12
        NumberEntries: 12
        SizeToPreAllocate: 480
        TotalNumberMessagesAllocated: 8
        LastMessageIndex: 8
        DefaultMessage: []
        MessageDelay: 0

```

C.10.5.8 Simulation Truth Message: *TrackList*

```

        Title: 'TrackList'
        ID: 8
        Enabled: 1
        NumberSenders: 8

```

```

        Data: [74x8 double]
      IndexStorageID: 1
    IndexStorageTimeStamp: 2
      ObjectID: [1 2 3 4 5 6 7 8 9 10]
    ObjectXYZPsiAlive: [1x60 double]
      ObjectType: 71
      ObjectMode: 72
    NumberEntries: 72
    SizeToPreAllocate: 480
  TotalNumberMessagesAllocated: 8
    LastMessageIndex: 8
    DefaultMessage: []
    MessageDelay: 0

```

C.10.5.9 Simulation Truth Message: *ChangeAssignmentFlagSelf*

```

        Title: 'ChangeAssignmentFlagSelf'
        ID: 9
      Enabled: 1
    NumberSenders: 8
      Data: [3x480 double]
    IndexStorageID: 1
    IndexStorageTimeStamp: 2
  ChangeAssignmentFlagTime: 1
    NumberEntries: 1
    SizeToPreAllocate: 480
  TotalNumberMessagesAllocated: 480
    LastMessageIndex: 19
    DefaultMessage: []
    MessageDelay: 0

```

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